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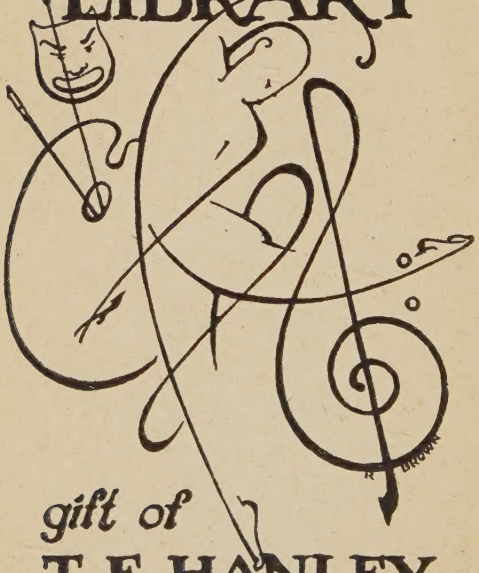

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THE ATOM

BY

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IN THE UNIVERSITY OF ABERDEEN

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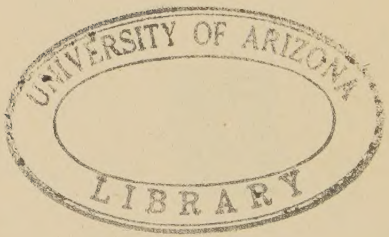

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NOTE

In this book the author has aimed at giving as up-to-date an account of the subject as possible, and has devoted a fair amount of space to the new wave theory of mechanics and atomic structure. This necessarily involves the inclusion of some rather tentative ideas, but even if some of these have to be revised, the new views bring an air of conviction which makes it reasonable to hope that their main outlines, at least, are final. As a physicist the author may have been tempted to curtail unjustly the space allotted to the chemical aspect. He hopes at least that he has said enough to induce the reader to study books on that part of the subject by men qualified to present its full beauty.

CHAPTER I

GENERAL OUTLINE

THE fundamental idea of the Atomic Theory is this, that objects ultimately consist of a large number of very small parts of a limited number of kinds. It thus stands in opposition to the doctrine that bodies can be indefinitely divided, even in theory. The root idea was propounded by Democritus, a Greek of the fifth century B.C., who may perhaps have been influenced by a still earlier philosopher, Leucippus. It was further developed by Epicurus and formed the fundamental idea of his school of philosophy, of which the best account extant is contained in the work of the Roman Lucretius, who set out the Atomic Theory in the dignity of six books of hexameter verse. For some reason this school of thought fell into decay even in classical times, and it was not till the early nineteenth century that Dalton revived it, and made it the foundation of chemistry.

The remarkable development of physics in the last thirty years is largely due to the modifications and extensions that have been made in the doctrine in its application to the latter subject, and it has recently been found to apply not only to ordinary matter, but in a modified form to the important and elusive quantity known as Energy. Before entering upon a consideration of the experimental facts on which the ideas are based, it may be as well to give in outline a sketch of the structure of matter as it is thought of to-day.

By "matter" in this connection we mean the ordinary stuff of the world as it appears to our senses: whatever can be felt, seen or smelt. As we shall see later, an exact definition is not easy, but the broad common-sense idea is enough for the moment. Matter of this kind can exist in three principal forms—solid, liquid and gaseous—which are well illustrated in the case of water, as ice, water and steam. For the moment this distinction of form may be regarded as of secondary importance. If one takes an ordinary object such as a lead pencil, it is obviously composed of several different materials, graphite, wood, paint, glue and perhaps others. A more searching

analysis by the method of chemistry would show some of these to be themselves mixtures of a number of simpler substances. In the case of the wood the complete analysis would be a severe strain on the resources even of modern chemistry, and we might have to be content with something less precise. But we believe that, given sufficient skill and knowledge, it would be possible to separate any object into what are called chemically pure substances. These are substances which show perfectly definite and regular properties, however they are obtained. It is believed that a piece of any such substance is composed of a very large number of exactly similar bodies called Molecules, and that each of these molecules is composed of a limited number of still smaller bodies called Atoms, which may, or may not, be all alike in a given molecule. The number varies from one to probably many thousands in the case of some of the very complicated molecules which occur in living matter.

It should be noticed that the word "atom" is here used in a rather special sense. Probably Lucretius would have called our molecules atoms, for they are the smallest part

which can exist, of their particular chemical species. The word atom means indivisible, and at the time this nomenclature was invented this sort of atom was believed to be actually the smallest entity capable of independent existence. Though this is now known not to be the case, an illogical nomenclature, as so often happens, is too firmly established to be changed. In what follows then, we shall use the word atom always in this special technical sense.

It has been found that all the numerous kinds of chemically pure substances, of which hundreds of thousands are already known, have molecules which can be constructed from ninety kinds of atoms, and of these ninety a large proportion are very rare, and hardly more than chemical curiosities. When a molecule consists of only one kind of atom, the substance is called an Element;[1] when there is more than one kind the substance is called a Compound. There are thus ninety elements known at present. But it is now known that each of these ninety kinds of atoms, or elements, has itself a structure and is composed

[1] This statement needs qualification owing to a complication explained on page 67 *et seq.*

of two primitive constituents called Electrons and Protons. Each atom in its normal state contains a certain number (varying from 1 to about 240) of electrons and an equal number of protons.

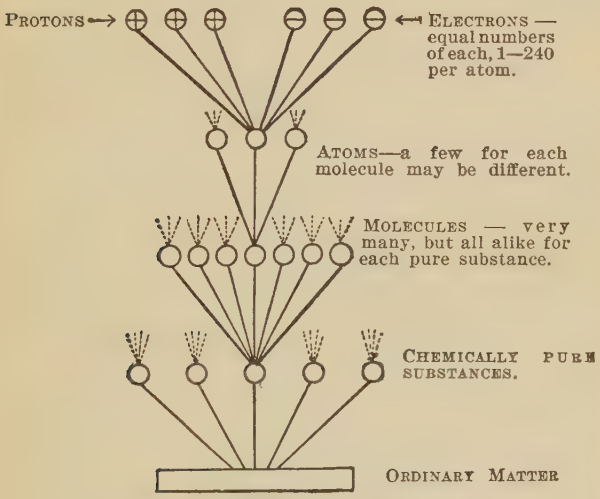
PROTONS
ELECTRONS — equal numbers of each, 1—240 per atom.
ATOMS—a few for each molecule may be different.
MOLECULES — very many, but all alike for each pure substance.
CHEMICALLY PURE SUBSTANCES.
ORDINARY MATTER

FIG. 1.—Family Tree of Matter.

We can thus form a kind of genealogical tree of matter—any piece of matter being composed of various chemical substances, each chemical substance of vast numbers of similar molecules, and each molecule of a limited

number of atoms, which may be of several kinds, and each atom of a number of electrons and protons. As far as is known at present, all electrons are identical, and so any two could be interchanged without visible effect, and the same apparently holds for the protons.

The most fundamental property of ordinary matter is generally considered to be that known as Mass. This is the property in virtue of which matter at rest requires a force to start it moving, and when in motion requires one to stop or turn its course. The mass of a body on the earth is proportional to its weight, i.e. the force with which the earth attracts it; but while weight would be quite different on the moon, for example, mass is inherent in a piece of matter, and is independent of its conditions. Electrons and protons have mass, the latter about 1,845 times as much as the former. Thus the mass of a piece of matter is mostly the mass of the protons which it contains.

In dividing the atom into electrons and protons we come to a new idea, for besides the possession of mass which they contribute to the structures made from them, they have in addition very strong electrical properties,

which are lost, or at least greatly weakened when they are combined to form atoms.

It is becoming more and more impossible to define electricity because it seems rather to be the fundamental idea, in terms of which everything else must be explained, and so cannot itself be explained without arguing in a circle. So it is with a dictionary. There must be some words whose meaning is taken as known. All one can do is to state instances of what are regarded as electrical effects, and to argue by analogy from them. Thus if certain substances are rubbed they acquire the power of exerting forces on one another. These forces are attractions when a pair of bodies have been rubbed together, and are repulsions when two similar bodies have each been rubbed on another of a different kind. Such attracting or repelling bodies are said to be Electrically Charged. Again, if a wire is connected to two metal plates of different kinds dipping in a suitable liquid, and forming what is called an electric battery, the wire is found to possess certain special properties. Firstly it becomes heated, an effect which may be very marked if part of the wire is fine, and secondly it acquires the power of deflecting a compass

needle placed near it. It is then said to be carrying an Electric Current. Since it has been shown that similar magnetic effects are produced by the motion of electrically charged bodies, it is reasonable to regard the electric current as due to the motion of electric charges in the wire although no motion is visible. This view is confirmed by other experiments.

Now electrons and protons show just these effects. When in rapid motion they can produce the magnetic effects of a current, and when absorbed by an otherwise unelectrified body they cause it to show electric attractions or repulsions. It is thus natural to speak of them as being electrically charged, but it must not be supposed that the charge is something super-added to them, as in the case of an ordinary material body, but rather that their electrical properties are a fundamental part of their constitution. By a survival from an old theory the two kinds of charges that a body can have are arbitrarily classified as "positive" and "negative." It turns out that a proton has the same kind of charge as a positively charged body, and an electron that of a negatively charged one. Thus two electrons repel each other, and so do two

protons, but an electron and a proton will attract.

For equal distances apart the attractions and repulsions are the same and it follows that if an electron and proton were put close together, the forces they would exert on another electron, or on another proton, at a considerable distance away, would practically balance. This is expressed by saying that the electron and proton have equal charges of opposite kind. The two charges put together are said to neutralize each other, just as + 1 and — 1 give 0. In this connection the use of the terms positive and negative has a justification. But the distinction between electron and proton is something more than merely one of sign. For example, the proton is more than a thousand times heavier than the electron.

A body which has a few more electrons than protons will thus behave as a negatively charged body, and one with fewer electrons than protons as a positively charged one. Since electrification usually, though not always, is caused by the transfer of electrons rather than of protons, a negatively charged body is one which has gained something, while

a positively charged one has lost something. The choice of sign has thus been unfortunate, but the names have now acquired such a strong vested interest that it is hopeless to think of changing them.

CHAPTER II

THE SPECTRUM

THERE is one means of investigation which, in various forms, has proved of such extraordinary value in the study of atoms, that it seems necessary to give a brief account of it before proceeding to explain how the results sketched in the last chapter have been reached. It is well known that if ordinary sunlight passes through a glass prism it is split up into a series of colours arranged in the order of red, orange, yellow, green, blue, and violet. These are in fact the colours of the rainbow, which is produced by light passing through rain drops acting in a manner similar to that of the prism. Such a band of colours is called the Spectrum of light. With a more elaborate instrument called the spectroscope the band of colours can be made clearer and more brilliant.

It was discovered in the first half of the nineteenth century that certain sources of

light, when examined by a spectroscope, show not a continuous band of light, but a number of bright lines separated by dark intervals. A line which appears in the region which would be yellow if sunlight were being examined is itself yellow, and similarly for other colours. A very important discovery was made when it was found that the number and position of these lines was characteristic of the substance emitting the light. Thus the

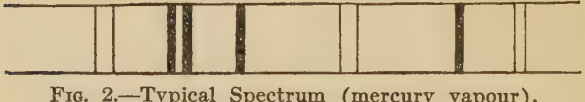

FIG. 2.—Typical Spectrum (mercury vapour).
[In reality for emission spectra the lines are coloured on a black ground. For absorption spectra they are black on a coloured ground.]

very intense yellow flame which is produced when common salt is inserted in a Bunsen burner shows a spectrum of two yellow lines very close together. These lines are due to the element sodium which is a constituent of the salt, and are observed whenever sodium is present in a flame under suitable conditions, and never in any other circumstances.

Corresponding spectra have been observed and tabulated for a large number of other

substances, and the spectroscope thus affords a very convenient method of determining what substances are present in a given body. In some cases it is the only method possible. For example, it is by this means that we are in a position to make statements as to the substances present in the stars. Sometimes the spectra are very complicated. That of iron contains tens of thousands of lines if suitable electrical methods are used to excite the luminosity.

Now there is good reason to believe that light consists in some way of undulations of the hypothetical medium called the Ether, which is supposed to fill all space. As in the case of waves on the surface of water, these ether waves may differ from one another in what is called the wave-length. That is to say, on the water analogy, in the distance from crest to crest, or from trough to trough. It is supposed that the action of the spectroscope is to separate the mixture of waves of different wave-lengths which may be present in the original light, into their constituent wave-lengths. Thus each wave-length has a definite colour, and the process of spectrum analysis consists in finding out what particular wave-

lengths are present in the light examined. The fact that a given substance has a definite spectrum means that, if it emits light at all, it emits light of certain definite wave-lengths. The exception is the so-called continuous spectrum, like that of sunlight, which is emitted by any solid or liquid hot enough to be incandescent. The characteristic spectrum is in fact only given by a gas or vapour.

If light from a substance emitting a continuous spectrum passes through a vapour, the vapour may absorb the kind of light which it would itself emit if heated or electrically excited. The spectrum of the transmitted light will then show black lines on a coloured background. Sunlight itself shows this effect owing to a layer of cooler gas surrounding the main incandescent mass of the sun. It is from the position of these black lines (Fraunhofer lines) that the nature of the substances present in the sun has been found. Such a black line spectrum is called an "absorption" spectrum, in contrast to the bright line "emission" spectrum.

Spectra are also formed when instead of a prism we use a piece of glass ruled with a number of fine lines extremely close together

—a grating, as it is called. The production of such gratings of the necessary fineness and accuracy—1,500 lines to the inch is quite usual—is largely the result of the ingenuity of an American physicist, Professor Roland, of Baltimore, much of whose work was done in the eighties of last century. Besides giving finer and more brilliant spectra, the grating has the advantage over the prism that it is possible to compare the wave-length of the light which appears in any part of the spectrum, with the distance between successive lines on the grating, and thus actually to measure the wave-length of the light.

The values so found are very small, of the order of $^{2}/_{100000}$ of an inch for green light. The red light has the longest wave-length, and the violet the shortest of the waves of ordinary light. It has long been known that radiations exist beyond both ends of the spectrum of visible light. In fact, what we call light is merely that small part of a vast range of radiations, similar in character but varying vastly in wave-length, to which the eye happens to be sensitive. The others are, so to speak, invisible colours.

The longest of these are the now familiar

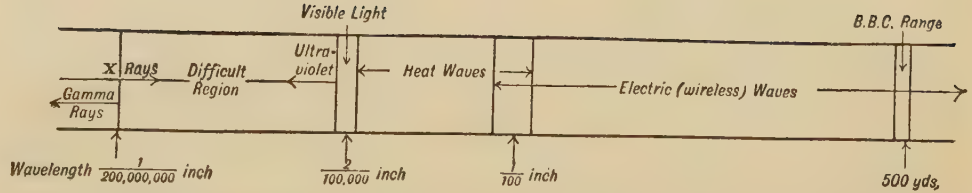

FIG. 3.—Range of the spectrum: equal distances correspond to equal *ratios* of wave-lengths.

wireless waves, with wave-lengths varying from thousands of yards down to some which have been produced in the laboratory, of a fraction of an inch in length. Then come a wide range of what are sometimes called heat radiations, though in fact all these waves cause heat when absorbed. They are also sometimes referred to as infra-red rays. Then comes the visible spectrum and then the spectrum of ultra-violet radiations which have recently come a good deal into public notice because of their medical value. Then comes a range of rays only very recently explored because of the experimental difficulty that all substances including even air, absorb the rays so strongly that they can only be studied in an almost perfect vacuum. Then come the X-rays with their wave-lengths round about $\frac{1}{10000}$ those of visible light. Then certain radiations from radium and similar substances known as Gamma rays. Finally, shortest of all, a form of radiation known as Cosmic rays, which apparently come to us from the depths of space. These last have a wave-length in some cases less than a million-millionth of an inch, though it should be admitted that this is a rather indirect estimate. The wave-lengths

of the X-rays, however, are known with great accuracy by a method which we shall have occasion to explain later, and have been of immense importance in disclosing the size and structure of atoms.

Although there is no essential difference between X-rays and the other radiations of the spectrum on each side of them, they have played such an important part in atomic physics that they deserve rather more detailed notice here.

Indeed the original discovery of X-rays by Röntgen in 1895 is perhaps the most convenient date to take as the starting-point for the modern investigation of atoms. The discovery was apparently half accidental. In a search for possible invisible radiations Röntgen had enclosed a tube containing air at a very low pressure in black paper, and he noticed when an electric current was sent through it, that a screen coated with a fluorescent mineral, and which was lying on a table at some little distance, shone out brilliantly. Such a screen might have been effected by ordinary ultra-violet light, but this would not have penetrated black paper, and Röntgen at once realized that he had discovered some new radiation.

Investigation soon showed that the radiation was one which could cast shadows if an obstacle was placed between the tube and the screen. The source of the rays was traced down to the place where a certain feature of the electric discharge (the Cathode Rays) hit something solid. The circumstance of their discovery showed at once that the X-rays possessed the property by which they are now most commonly known, of passing through substance opaque to ordinary light, and it was found that the transparency or otherwise of an object depended mostly upon its density. Thus the glass of the tube itself must have stopped more of the rays from emerging than the black paper with which it was covered.

It is this power of indiscriminate penetration which has made the rays of such value in surgery; for the comparatively light fleshy parts of the body are nearly transparent to the rays while the much denser bones cast a black shadow. But from the point of view of physics other properties are of more importance. Thus the rays have the power of causing the air through which they pass to become for a time a conductor of electricity. Air in ordinary circumstances, it may be said, offers

the greatest resistance to an electric current, and nothing will pass until the electric force becomes so great as to cause a spark, or miniature lightning flash.

Although the X-rays were not the only means known, even then, of making air conducting, they were much the most convenient, and their discovery made possible the long series of researches on the conduction of electricity through gases which went far towards disentangling the relationships of electricity and ordinary matter.

CHAPTER III

THE ATOM IN CHEMISTRY

THE essential difference between elements and compounds referred to in the first chapter seems first to have been recognized by a brilliant Irishman, Robert Boyle, one of the original Fellows of the Royal Society, who was described by one of his contemporaries as "Father of Chemistry and brother of the Earl of Cork." It thus antedates the modern atomic theory, which may be regarded as starting with Dalton's work first published in 1803. The elements which played a large part in Greek and mediæval philosophy, and in the theories of the Alchemists, at first sight seem to refer to what we now call matter, being as they were earth, fire, air and water. But they were really regarded much more in the light of qualities, than as material constituents of the bodies possessing them.

It was not till the time of Lavoisier, whose

needless execution was one of the greatest blots on the French Revolution, that the importance of weight in chemistry came to be fully realized, and with it the idea of a substance composed of constituents whose weights added together should equal its own. It follows from this view that if any substance invariably increased in weight as a result of chemical action it must be an element, while if it lost in weight by such a change it must have been a compound decomposing into its elements or being changed into a lighter compound. But this rule, as Lavoisier fully realized, is inadequate by itself, for there is always the possibility that what one takes to be an element may really be only a very persistent compound which has defied all efforts to split it up. Indeed, some of the elements in Lavoisier's list were compounds of this kind.

Dalton, using the atomic hypothesis, postulated the existence of molecules and atoms much as we have described them above. He was at once led to certain laws which must be true if the atomic hypothesis is true, and which are capable of experimental test. Thus if a substance is composed of molecules all alike, and therefore each containing the same

number and kind of atoms, then, however that substance has been made, it must always contain the same proportion by weight of its constituent elements. This he called the Law of Constant Proportions. Secondly, if two compounds are known to exist between the same two elements, the proportions by weight of the elements in the two cases must bear a simple relation to one another. This can be illustrated by one of Dalton's own examples. There are two gases which, as Dalton had reason to believe, and is actually the case, are compounded from the same two elements, Carbon and Oxygen. Their molecules, in fact, consist in one case of 1 atom of carbon and 1 of oxygen, in the other of 1 of carbon and 2 of oxygen. It follows that the second has twice as much oxygen in proportion to its carbon as the first. And this would be true whatever the weights of the atoms of carbon and oxygen. If it had happened that the first had contained, say, 2 of carbon and 1 of oxygen, the relative proportions would have been 4 to 1 instead of 2 to 1. Thus the different weights of carbon which combine with say 100 grammes of oxygen in the two compounds must bear a relation to each other

like that of simple whole numbers. This is known as the Law of Multiple Proportion.

Finally he announced a more complicated Law of Reciprocal Proportions. This may be illustrated in the simplest case as follows. Suppose the elements A, B, C, can each combine in pairs so that they form compounds whose molecules consist in each case of 1 atom of each constituent, i.e. AB, BC, CA. Then, if a, b, c are the weights of the different atoms, $\frac{a}{b} \times \frac{b}{c} = \frac{a}{c}$. Therefore the proportion by weight of A which combines with C can be found by multiplying together the proportion of A which combines with B, and the proportion of B which combines with C. With the aid of a pencil and paper the reader would have no difficulty in satisfying himself that in the more complicated case, when the molecules contain more than one atom of each kind, a similar result holds good, except that the answer must be multiplied by the ratio of whole numbers, depending on the number of atoms of the different kinds in the various molecules.

Some instances of this law had already been discovered experimentally for combinations

between acids and alkalis, but Dalton was the first to explain its theoretical significance. These laws have since been verified for a number of compounds, in some cases with very great accuracy, and no definite exceptions have ever been found. It should be noticed, however, that the simple relations between the proportions in which different elements combine would, in the atomic theory, be "simple" (i.e. the ratio of small integers) only if the number of atoms concerned is small. In some of the complicated organic compounds this ceases to be the case, but the proportions found are always such as might be expected from the probable atomic constitution of the molecules, judged from the way in which they have been formed from simpler substances and from their other chemical properties. Thus the laws must be regarded as experimentally true, and they form in fact the basis on which all subsequent chemical progress has rested.

A problem which Dalton studied with great care was to find the relative weights of the atoms of different elements. If all compounds contained only one atom per molecule, of each of the elementary constituents, this

problem would be an easy one. The relative weights of the atoms would simply be the relative weights of the elements which combined to form the compound. But the very existence of a law of multiple proportions shows that this is not always the case, and when, for example, two elements combine together to form several compounds it is not obvious at first sight which, if any, of these has a molecule consisting of only one atom of each element.

In fact, the process of determining the relative weights of atoms exercised chemists for nearly sixty years after the foundation of Dalton's theory, and in some cases indeed the uncertainty lasted even longer. To give a concrete instance of the difficulty, Dalton thought that a molecule of water contained 1 atom of hydrogen and 1 of oxygen. If this were the case, since 8 parts by weight of oxygen combine with 1 of hydrogen to form water, an atom of oxygen would weigh 8 times as much as 1 of hydrogen. It is now known that the water molecule contains 2 atoms of hydrogen to 1 of oxygen, and the weight of the oxygen atom is thus 16 times that of the hydrogen.

Controversy on this question, and on others like it, occupied a great deal of the time and energy of chemists of the first half of the nineteenth century. The evidence available at the time afforded nothing better than a balance of probability between the various views, and a definite decision seemed almost impossible. So much so that some chemists were in favour of abandoning the search for atomic weights altogether, and of considering only the equivalent weight, or combining proportions, which were a matter of direct experiment. Unwillingness to accept a theory which goes beyond the immediate facts of experiment is very characteristic of a certain type of mind, which seems especially common in Germany. The recent history of physics shows several examples. While this attitude is undoubtedly very valuable as a check on wild theorizing, there is a danger that such a negative point of view may discourage useful lines of thought. The inspired guesses from which all great scientific advances arise are much more likely to come from a vivid concrete picture than from a purely logical statement of the facts. Certainly it would have been a great calamity for chemistry if the atomic

conception had been abandoned in favour of a colourless statement about combining weights.

Fortunately, substantial agreement about atomic weights was eventually reached as a result of the application of a principle originally enunciated by Avogadro shortly after Dalton's work. The importance of this idea was overlooked for nearly fifty years, by some curious blindness of which there are other instances in science, and it lay unnoticed till resurrected by Cannizaro in 1858. The principle is this—that equal volumes of all gases under the same conditions of temperature and pressure contain equal numbers of molecules. This principle is not capable of experimental proof, or at least was not when it was originally used, but is a consequence of a theory of gases according to which the pressure of a gas is caused by the impact of the molecules on the walls of the vessel containing it. Each molecule is supposed to move independently of the others, with a speed depending on the temperature of the gas—the whole gas forming a chaos of molecules rushing about at random in all directions, and perpetually changing their motions as the result

of collisions with one another and with the walls of the vessel.

Thus, when two gases combine together to form a third, the relative volumes of the two and of their product give the relative number of molecules in them. For example, 2 volumes of hydrogen and 1 of oxygen combine to give 2 volumes of steam, i.e. 2 molecules of hydrogen and 1 of oxygen give 2 molecules of steam. Now each molecule of steam must have at least 1 oxygen atom, but it only has available half a molecule of oxygen to draw on, hence the molecule of oxygen must have at least 2 atoms. (Though, as far as this experiment goes, it might equally well have 4 or 6 or any even number.)

Thus one has to face the extra complication in the theory that the molecule of an element is not necessarily simply 1 atom. This fact, indeed, was the cause of most of the difficulty in unravelling the relative weights of atoms. But the above experiment does not tell us anything about the number of hydrogen atoms in a molecule, since in this case 1 molecule of hydrogen gives 1 molecule of steam, and all we can tell therefore is that there are the same number of hydrogen atoms in a hydrogen

molecule and in a steam molecule. A second experiment, however, decides it. One cubic foot of chlorine can combine with 1 of hydrogen to form 2 cubic feet of gaseous hydrochloric acid. Hence by a similar agreement to that in the case of oxygen the molecule of hydrogen must contain at least 2 atoms, and so also the molecule of water. It will be noticed that in all these cases we have had to say "at least." By arguments of this kind it is never possible to prove the exact number. One can only find the smallest number of atoms in a molecule which is compatible with all the observed facts. As a matter of fact there is no reaction in which it is necessary to suppose that either oxygen or hydrogen has more than 2 atoms in the molecule, and this number is therefore assumed to be true for reasons of simplicity; an assumption which has since been amply confirmed by evidence of a quite different character. The necessity of this restriction is obvious if we consider that if, for example, hydrogen atoms always went in pairs in every conceivable compound, the pair of atoms would be in fact the effective "atom" for all chemical purposes. To prove from chemical evidence that hydrogen has

only 2 atoms in a molecule is a typical case of the proof of a negative. We have to show that no case to the contrary ever exists. It is rather like a man trying to prove that witches cannot exist, whose conclusions would be completely upset by a single perfectly authenticated instance of one seen in the air on a broomstick!

We have thus proved, subject to the above caution, that the molecule of steam contains 2 atoms of hydrogen and 1 of oxygen. It follows from the composition of steam by weight, namely 8 of oxygen to 1 of hydrogen, that the weight of an oxygen atom is 16 times that of a hydrogen. By arguments on the same general lines as the above, though modified to suit various cases, it was possible to determine the relative weights of all the known elements, though there was occasionally some doubt in the case of elements which formed no gaseous compounds.

Dalton took as the standard the weight of the hydrogen atom which he took as unit, and for some time chemists followed his lead. More recently oxygen has been taken as standard, but instead of counting its weight as unity it is taken as 16, the nearest whole

number to the value 15.9 which it had on the other scheme. There is accordingly not much difference between the numbers for the same element on the two methods of reckoning. On the oxygen scale the weight of the hydrogen atom is 1.0078 instead of exactly one. This change was originally made as a matter of convenience because more elements combined with oxygen than with hydrogen, and the weights being thus often determined with reference to oxygen, it was inconvenient to have to change them all whenever a more accurate determination was made of the relative weights of hydrogen and oxygen. The change was a fortunate one, as it now appears that the weight of hydrogen is an exception to a general rule which we shall discuss later.

It will be noticed that in all we have said so far only relative weights have been considered. There is no evidence from ordinary chemistry as to the actual weight or size of any single atom, except of course that they must be smaller than the smallest speck of material which can be handled in chemical processes. Indeed, it is only in the last thirty years that any really accurate knowledge of the absolute sizes and weights has been attained,

and this knowledge has come from the side of physics.

It was observed at a fairly early stage that certain of the elements showed strong family resemblance in their chemical behaviour, and that in some cases at least there were approximate relations between the atomic weights of the members of these families. A great insight into the connection between the properties of different elements was gained by the Russian chemist Mendelejeff, who discovered what is called the Periodic Table of the elements. He found that if the known elements were arranged in the order of the weights of their atoms, atoms with similar chemical properties reappeared at periodic intervals. Thus leaving hydrogen aside, the second lightest element, the gas helium, which is peculiar in forming no chemical compounds, is resembled in this respect by neon, which is 10th on the list. The 3rd element, lithium, a soft white metal very easily tarnished, is closely resembled both in physical and chemical properties by sodium, the 11th on the list. In the same way the 4th and 12th elements, the 5th and 13th, 6th and 14th, 7th and 15th, 8th and 16th, and 9th and 17th elements all closely

resemble each other in pairs. That is to say, the first of each of these pairs of elements has a sister element 8 places further along in the list. This scheme continues for another set of 8 elements, the 18th element being similar to the 2nd and 10th, the 19th to the 3rd and 11th and so on. After this, however, the scheme becomes more complicated, and it is not till 18 elements further on that we return to the properties of numbers 2, 10, and 18. There are 2 periods, as these series are called, of 18 elements, the second fairly closely repeating the first, and then come still further complications which it is hardly necessary to consider in detail. The complete table in its most modern form is shown in the Appendix. The lightest element hydrogen has no sister elements and is therefore omitted from the table.

When Mendelejeff first published the table he had to assume the existence of certain gaps in order to make the periodicity fit, and he was bold enough to predict the existence of elements to fill these gaps, describing in advance what their properties would be found to be, by considering those of their sister elements. His predictions were trium-

phantly justified in certain cases by the discovery of elements with just these properties and whose atomic weights made them fit into the gaps.

Nevertheless down to 1913 there were still considerable difficulties in the table. In two cases elements were in the wrong order, that is to say an element which, to fit the table, should have had an atomic weight greater than another, actually had one slightly less. There were still a good many gaps, and the whole arrangement in the latter part of the table, where the regularities are for the most part less well marked, was rather uncertain. The removal of these difficulties was largely due to the genius of the young English physicist Moseley, whose death at Gallipoli was one of the greatest losses which science suffered during the War.

The development arose as a consequence of work on X-rays, and is a very good illustration of the way in which progress in one branch of science reacts upon another. One often sees instances in science of progress in one direction slowing down and coming almost to a standstill, until it spurts forward again as the result of discoveries made in some quite different

quarter. This indeed causes one of the great difficulties in writing a book such as this. Each line of progress uses the results obtained in the others, and this makes it difficult to describe any one part of the subject without referring forward to ideas which have not yet been explained.

The particular advance which made it possible to complete the order of the periodic table was the discovery of the German physicist von Laue. He found that it was possible to use a crystal to do for X-rays much what a ruled grating does for visible light. As we have already stated, it had long been considered nearly certain that X-rays are a form of waves, but it had never been possible to measure the wave-length, or to make the hypothesis absolutely clear from dispute. We have seen that the measurement of waves of light depends on getting a grating on which the lines are ruled at intervals, which though greater than the wave-length of light are not out of all proportion to it. Now optical gratings were already about as finely ruled as is mechanically possible, and X-rays have only, as we now know, about $\frac{1}{10000}$ of the length of visible light.

The problem seemed insoluble,[1] but Laue had the brilliant idea that a crystal is a regular arrangement of atoms, and that these atoms and the spaces between them would behave for very short waves in much the same way as the lines and spaces of a ruled grating do for light waves. The essence, indeed, of all crystals is that the atoms and molecules in them are built up in a perfectly regular formation characteristic of the kind of crystal. One may think of them as very much like a body of soldiers drawn up in close order, while a non-crystalline substance would correspond to a disorderly crowd. Just as there are many regular formations in which the soldiers of a battalion can be drawn up, so there are many possible types of crystal structure, but all have this property of regularity. The pattern repeats at stated intervals in all directions, like the pattern on a wall paper.

Now when X-rays are passed through such a crystal it can form a spectrum of them like the spectrum formed of light by the grating.

1 Recently it has been found possible to measure the length of X-rays by using mechanically ruled gratings with the rays striking at a very small glancing angle.

There are, it is true, certain secondary but important differences in the analogy, due to the fact that the atoms in the crystal are arranged in space, i.e. in three dimensions, while the lines of the grating are confined to a plane, but this does not alter the fundamental possibility of producing X-ray spectra like the optical spectra.

By 1913, when this experiment was suggested, sufficient was known of the actual sizes of atoms to make it possible to determine their spacing, and hence to calculate the actual wave-length of the X-rays from the position of their spectra. It was found that X-rays, as had been suspected, can form two kinds of spectra, one continuous like the light from an incandescent solid, and another consisting of bright lines characteristic of the particular element, just as optical spectra are characteristic. But the X-ray spectra have one immense advantage over the optical spectra. While the latter are generally extremely complicated, involving a large number of lines, in some cases thousands, whose wave-length does not vary in any simple manner with the weight or even the chemical nature of the atom, the X-ray spectra form a perfectly regular gradu-

ation. Thus Moseley found that each of the elements he examined showed two main lines, and that the wave-length of these strong lines varied in a perfectly regular manner with the position of the element in the periodic table. He found, in fact, that a certain quantity connected with the wave-length, to be precise the

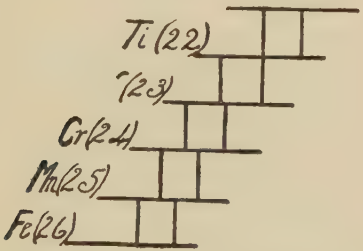

FIG. 4.—X-ray spectra of five successive elements superposed to show the steady change in the position of the (vertical) spectral lines.

[The numbers in brackets are the atomic numbers.]

square root of its reciprocal, changed by the same amount as he passed from one atom to the next in the periodic table, although the differences in atomic weight were sometimes large and sometimes small. He found, further, that in the two cases where the order of atomic weights made elements come in the

wrong order in the periodic table, the order of their X-ray spectra agreed with that of their chemical properties. He was also able to show that certain gaps existed where there was a jump of twice the usual amount between the spectra of succeeding elements, and concluded that there were elements missing. In this way he was able to arrange the elements in a perfectly definite order based on their X-ray spectra which agreed extremely well with their chemical properties, even in the case of the heavier elements where the regularities we have previously described became less marked. He had to suppose in all 92 elements (or rather 91 steps) from hydrogen, the lightest, to uranium, the heaviest element. Of these possible elements 6 were missing at the time, of which 4 have since been discovered, in most cases by examining the X-ray spectra of suspected materials. The remaining 2 occur among the radio-active elements which are unstable, and it is possible that even if originally present in the earth they may long ago have ceased to exist. On the other hand it may merely be that they wait discovery. To describe this ordering of the elements the term Atomic Number was introduced, being

simply the number in the series, hydrogen 1, helium 2, up to uranium 92.

To attempt to describe the innumerable ways in which the atoms of the different elements can combine to form molecules of compounds would be to write a treatise on chemistry. However, there are one or two general principles which are of great importance, and which can be stated fairly shortly.

In the first place by no means any two elements can combine. The majority of elements are metals, and these for the most part when melted together yield alloys which are generally only mixtures capable of existence in any proportion, or at least any proportion within wide limits. Sometimes, it is true, definite compounds are believed to occur, but these are usually only distinguishable with difficulty from the range of mixtures. The non-metallic elements can combine together, and with the metals, with greater freedom. Compounds of most possible pairs are known, though there is one group of elements, the inert gases, which combine with nothing. On the other hand, a few elements may form many compounds. Thus an enor-

mous range of compounds is furnished by the compounds of carbon with hydrogen, oxygen, nitrogen, chlorine and its sister elements. These form the great bulk of the compounds constituting living matter, and their study is known as Organic Chemistry, though a very large proportion can now be made in the laboratory. The number of such compounds known runs into hundreds of thousands, and it is here that we meet with most of the more complicated molecules, some of which contain hundreds of atoms. Otherwise compounds of more than a dozen atoms are rather exceptional, and many very important chemical substances contain only 2 or 3.

But even in the realm of organic chemistry atoms cannot be thrown together haphazard to form a molecule. There are certain fairly definite rules known as the laws of Valency. These can be represented in picturesque form by imagining each atom provided with a certain number of loose tags of string attached to it. A compound is formed by tying the atoms together with these pieces of string and the rule is that no loose ends must be left. (It is rather an open question whether in certain cases you may be allowed to tie together two

tags belonging to the same atom, but even if permissible this is at least exceptional.)

A carbon atom is supposed to have 4 strings, hydrogen 1, oxygen 2, chlorine 1, and nitrogen may have 3 or 5 according to taste. The chemists express this by saying that carbon is tetravalent, hydrogen monavalent, oxygen divalent. It will be seen that this imposes very considerable restrictions on the possible molecules; thus if a single carbon is to combine with hydrogen it will need 4 atoms to use up its strings and can attach no more. If 2 carbon atoms are present, then they may be tied together by 1, 2, or 3 pairs of strings, leaving the remainder free to attach hydrogen atoms. Compounds are known corresponding to all these, the last one being acetylene. The very large molecules are, in fact, generally made on the basis of a long string of carbon atoms, often including rings of 6 tied together in a peculiar fashion, the exact nature of which has caused an immense amount of chemical controversy. This is the so-called Benzene Ring.

A very similar rule applies in inorganic compounds, especially those which are formed by the union of a metal and one or more non-metals. The metals can be grouped accord-

ing to valency, those of the same valency being for the most part sister elements in the periodic table. Thus there is one group of monovalent metals which includes sodium and potassium, another group divalent, and others trivalent including aluminium. If a monavalent metal combines with chlorine it does so atom to atom because each have one string, but it needs 2 monavalent atoms to combine with 1 of oxygen. On the other hand, a divalent element will combine with oxygen atom for atom, but needs 2 chlorine to satisfy it. There are, however, more difficulties and exceptions to the rules of valency in inorganic than in organic chemistry. Several of the metals, including some of the commonest such as iron, lead, and copper, can show 2 different valencies. In some cases the resulting compounds can be easily distinguished by colour. Some compounds could only be fitted in to the theory of valency (at least in its older form) by rather drastic and improbable assumptions. However, the growth in knowledge of atomic structure is already making the interpretation of the theory a good deal easier, although somewhat modifying the ideas involved.

The question of how far there is any

physical reality in any way corresponding to our wholly imaginary pieces of string must be left to a later chapter. We may mention however, that models made of the molecules on these lines have been capable of explaining many of the properties of inorganic substances. For example, atoms, which on this view would be placed close together in the molecule are more likely to take part jointly in a reaction with an outside molecule than if they were far separated. Structural formulæ, i.e. diagrams showing the relation and connection of the atoms in the molecules, play an indispensable part in the study of organic chemistry.

In fact, the immense progress of organic chemistry based on these ideas is the strongest evidence we have yet had that atoms have a real individual existence. It must be noticed that while Dalton's laws are completely explained on the atomic hypothesis, it is not logically necessary to believe in atoms merely because one accepts the laws. They might be regarded simply as an expression of the way in which different kinds of matter can react chemically. Indeed, as late as the end of the nineteenth century a distinguished German scientist preferred so to regard them.

The final proof has come from the domain of physics. So much has physics in the last thirty-five years become involved in the atomic ideas which before that time were mostly the preserve of chemistry, that the newer physics is sometimes distinguished from the older by calling it Atomic Physics. In contradistinction the older science, which dealt for the most part with the behaviour of matter in bulk, is called Molar Physics. The division is, of course, not perfectly sharp in point of time but the last decade of the nineteenth century saw a complete change in the general line of progress of physics. This change came about largely as the result of the study of the passage of electricity through very attenuated gases. The discovery of the electron was the first big step forward.

CHAPTER IV

THE ELECTRON

The early experimenters on electricity had no reason to regard electric charges as other than continuously variable. They spoke and thought in terms of an electric fluid, or sometimes fluids corresponding to the two kinds of charges; being influenced, no doubt, in this terminology by the ease with which electric charges can pass through metals and other conductors. They do not appear to have supposed that such electric fluids were in any sense atomic in structure. The first experiments to suggest that there was a natural unit of electric charge were those of Faraday on what is called Electrolysis. If an electric battery is made to drive a current, through a solution in water of one of the class of compounds chemically termed Salts, the salt is decomposed and the products of decomposition appear on the metal plates which lead

the current in and out. This is the fundamental principle used in electro-plating. The two metal plates are called Electrodes. The one connected to the end of the battery which would have a positive charge is called the Anode, while that connected to the negative side of the battery is called the Cathode. Salts are compounds of metals with non-metallic compounds, and it is found that the metal is deposited on the cathode while the non-metallic part goes to the anode. In many cases this non-metallic part reacts with the water after liberation, and so cannot be collected in its original form, being usually replaced by a chemically equivalent quantity of oxygen. In some cases the metal also reacts after liberation at the cathode, and hydrogen is produced instead. But metals such as silver which are not attacked by water are deposited on the cathode in the solid state and form a coating on it.

These facts had been known for some time, and, indeed, Faraday's old master, Sir Humphry Davy, had used the electrolysis of molten salts, which show an effect similar to the above, to isolate the metals sodium and potassium. Faraday applied quantitative

measurements to the process, and found a result which may be expressed in modern terms by saying that the weight of different metals deposited by a given current in a given time, is proportional to the atomic weight of the element divided by its valency. One can see at once that this is precisely the result which would occur if the atoms of the metal carried the current, and if each atom carried a charge proportional to its valency. The charge carried by a monavalent atom, e.g. silver, would then form a natural unit of charge. Since the liquid is in the same circuit as the wires from the battery and thus carries the same current, and the current in these wires shows no abnormality, it becomes highly probable that all currents, and hence probably all charges, are composed of units of this kind. Since the metal atoms move to the negative pole the charge on them is presumably positive. If a positive charge leaves the solution, an equal negative charge must leave it also, or the solution will acquire an increasing negative charge as the electrolysis proceeds, which is not, in fact, the case. Thus the non-metallic part must also carry a charge, and the same law of units is found

to hold for it also, though the investigation is somewhat complicated by the chemical reactions referred to above.

Further, since the salt disappears from the solution without leaving an excess of either constituent, and without leaving a residual charge, the units in the two cases must be equal of opposite kinds.

While there is strong presumption here for the existence of atoms of electricity, it does not amount to proof any more than does the chemical evidence for atoms of matter. The solutions certainly behave as they would behave if electric charges were divided into units in this manner, but alternative explanations are quite conceivable. For some reason much less stress was laid on the unitary nature of electricity than on the atomicity of matter, and for fifty years nothing of fundamental importance was added to Faraday's view. To complete the proof it was necessary to find one of Faraday's unit charges disentangled from the atom that bore it.

The advance came from the study of the passage of electricity through gases, as Faraday's original idea came from the study of liquids. A gas in a normal state does not

conduct electricity, but if the electric tension is made sufficiently great the insulating properties of the gas are broken down and a spark passes. This happens with greater ease if the gas is at a reduced pressure, and in the seventies and eighties of last century much experimental work of a qualitative kind was done on these discharges, which are generally luminous and often show beautiful colour effects.

Among other phenomena studied were those of the cathode rays, which had been discovered as early as 1859. They appear as a beam of light which starts from the cathode and usually diverges from it. Where it hits the glass walls of the tube it produces a green fluorescence. The rays are bent if a magnet is brought near the tube in which they are formed. They require a fairly low pressure before they show up well. The pressure should not be more than $\frac{1}{10000}$ of that of the atmosphere, and in experiments on the rays is usually much less. These rays had excited a good deal of interest from the time of their discovery, and opinion was divided as to whether they were more properly regarded as charged particles or whether they were more allied to the

Hertzian or wireless waves which had then been recently discovered. But the extraordinary importance which these rays were to have in the history of physics was not fully realized until Sir J. J. Thomson in 1897 was able to prove that the rays carried an electrical charge far larger in proportion to their mass than that of any other known body. The method consisted in first measuring the extent (p p', Fig. 5) to which the rays were deflected by a magnet of known strength, and then pulling the rays back to their original direction by allowing them to pass between two plates (D and E, Fig. 5) connected to the poles of a powerful electric battery. The electric force on the rays is thus balanced against the magnetic, and exactly compensates it for a certain strength of battery. A mathematical investigation shows that from the results of these two experiments it is possible to deduce the proportion of electric charge to mass for the rays and also their velocity. The importance of this proportion is seen when we remember that in Faraday's experiments the mass carrying a given charge is a measure of the atomic weight of the substance.

It is important to notice that, since the cathode "rays" carry a charge, they are fundamentally different from light and its allied radiations described in Chapter II. Thus they have no place in the spectrum (Fig. 3). The word "ray" as applied to them only implies a tendency to go in straight lines unless deflected by some special cause.

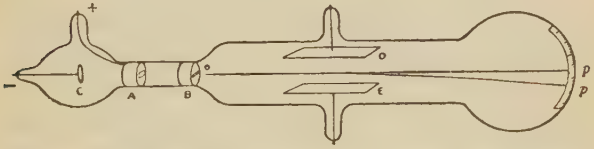

FIG. 5.—The lines of force of the magnet (not shown) are perpendicular to the paper.

From Sir J. J. and G. P. Thomson, "Conduction of Electricity through Gases," Vol. 1; Cambridge University Press, 1928.

If then cathode rays have a charge more than a thousand times greater than the atom of hydrogen, the conclusion suggests itself that they are particles of less than $\frac{1}{1000}$ of the mass of what was till then the lightest known object. The evidence is not complete. It is possible that the abnormality is due rather to the large charge than to the small mass, but a strong argument against this is that the proportion of charge to mass is the same for all cathode rays, whatever the gas

through which they pass and whatever the material of the cathode from which they start. Now it is very unlikely that if, for example, a cathode ray were really an atom of hydrogen with more than a thousand of Faraday's unit charges upon it, that this number will always be the same in very varying conditions. Further, Lenard had shown that cathode rays could pass through thin sheets of metal which were perfectly gas-tight and without leaving any trace of their path. It did not seem very likely that atoms would be able to pass through a solid in this way. But the final proof requires the determination of the actual charge. While this could not easily be done for the cathode rays, J. J. Thomson was able to show that certain particles emitted by metals under the action of ultra-violet light showed the same abnormally large proportion of charge to mass as the cathode rays. These particles, if emitted in air, soon attach themselves to the molecules, and in this state it is possible to measure their charge. The measurement showed a value in good agreement with the value then accepted for Faraday's unit of charge. It is true that this last was not known with any great accuracy, for

though it is easy to measure the total charge carried by a given volume of hydrogen, it is difficult to tell how many molecules this contains. It is hardly worth while describing the methods by which various estimates of this number had in fact been made, as they have been entirely superseded by methods based on the electron itself. But though they left much to be desired in accuracy and certainty, there could be no possible question of a thousandfold error, and indeed the agreement was surprisingly good.

This work made the first definite breach in the view that the chemical atoms were the ultimate smallest constituents of the universe. Not merely were the particles forming the cathode rays lighter than the lightest atom, but since they were independent of the varied materials from which they could be derived, it became practically certain that they formed a universal constituent of all forms of matter. The name electron is now universally given to these particles, and it is a curiosity of history that it was originally suggested by Johnstone Stoney in 1891 as a name for Faraday's unit charge, years before the experimental proof of its existence as a separate entity.

But whatever the structure of atoms may be, and from this time on it may be said to have become the central question of physics, it is at least certain that they must contain something besides electrons. All electrons are the same and have the same negative charges, and any two negative charges repel each other. For example, two pinheads, if each were made wholly of electrons, would repel each other if placed near together with a force greater than the weight of a body equal to the earth. Since, of course, no such effect occurs with pinheads or any other ordinary matter, there must be a positively charged constituent to neutralize the electrons. This positive constituent appears to have approximately the mass of a hydrogen atom, which the latest measurements show to be about 1,844 times that of an electron. A hydrogen atom is, in fact, formed of one electron and one positive unit. Sir Ernest Rutherford has named this positive unit the Proton.

Since the hydrogen atom is neutral the charge on the proton must be numerically the same as that on the electron but with opposite sign, so that when added together they

cancel. Every other neutral atom must thus contain equal numbers of electrons and protons. But it is, in fact, possible by various methods to detach one, or sometimes more, electrons from an atom, leaving it with a resultant positive charge. Also some atoms, but not all, are capable of picking up an extra electron if one is present free in the neighbourhood. This, of course, gives them a negative charge. Such charged atoms are known as Ions, and are, in fact, the carriers of the current in Faraday's experiments on liquids, so that we see why the charge carried by an atom is always a multiple of a natural unit.

The evidence that the proton is indeed the proper unit to choose is largely negative. No positively charged body has been obtained with smaller mass, and no one has ever succeeded in removing more than one electron from a hydrogen atom. If the hydrogen atom really contains only one electron, then the residue after it is removed will be a body with a positive charge numerically equal to that of the electron, and thus it is probably the unit we are seeking. Of course there can never be any proof that the proton, or for that matter the electron, does not, in fact,

consist of a number of smaller units. All we can say is that there is no sign of either splitting up in any of the experiments which have so far been made.

There is one consequence of the above view which is very interesting as leading us back to a theory, once popular but for long discarded. If every atom is made up of equal numbers of electrons and protons, the weights of all the atoms will be multiples of the weight of the atom of hydrogen. In other words, atomic weights reckoned in terms of hydrogen would all be integers. Now this view had been suggested by Prout in the very early days of Dalton's theory. The idea had obvious attractions and a considerable vogue, but with increased accuracy of measurement it became clear that the facts were against it. Many elements showed atomic weights which were definitely not integral. For example, the atomic weight of chlorine is 35.5, but it is a curious fact that a surprisingly large proportion of the atoms, including many of those whose atomic weights were known with the greatest accuracy, did obey a whole number rule. There were more than could be explained by mere chance, and yet there were

plenty of undeniable exceptions. The explanation has come since the War as a result of the remarkable experiments of Dr. Aston. He has been able to show that the atoms of some, but not all, of the elements, are of more than one kind. Thus, to take the particular case of chlorine. There are some atoms with a weight of 35 and others with a weight of 37. It may be said that this is equivalent to stating that chlorine is really a mixture of two elements, and from one point of view this is a just interpretation. But the two kinds of chlorine have properties so nearly identical that it has been decided that the more appropriate nomenclature is to continue to speak of chlorine as an element, and to coin a new name for the two constituents. They are called Isotopes. The identity in properties is, in fact, so nearly complete that it is only with the utmost difficulty that it is possible to produce even a slight variation in the proportions in which they naturally occur; to produce, that is to say, a brand of chlorine containing, for example, rather more of the 37 and rather less of the 35 constituent than is normally found. All the ordinary chemical means which are used to separate one element

from another are quite powerless to effect any change in this proportion, and it is only by using methods which depend directly on the weights of the atoms that it is possible to do so.

This discovery of isotopes introduces a rather embarrassing complication when one tries to make a simple statement of the atomic theory. In giving the rough sketch which forms the first chapter of this book it seemed better to ignore it, so that some of the statements there, as remarked in a footnote, are not strictly accurate. It is found that a considerable proportion of the elements are mixtures of isotopes, some having as many as eight or nine. It is now clear why some, but not all, of the elements show integral atomic weights. Those which do so are those which have only one kind of atom. When there are isotopes, the measured atomic weight is merely a mean value which will depend upon the proportions in which the isotopes are mixed. At present nothing is known of the causes which result in some atoms having many isotopes and others being single, nor is it known why the isotopes, when they exist, occur in the proportions in which they are

actually found in nature. The important fact is that the atomic weight of each isotope, to a fairly high degree of accuracy, is a whole number, in excellent agreement with the view that they are made up in each case of a whole number of electrons and protons. Curiously enough, the most marked exception to this rule is hydrogen itself. It will be remembered how we explained that it was now usual to take the atomic weight of oxygen as 16 exactly, and the others in proportion. It is on this scale that the whole number rule holds good. Hydrogen comes out as about 8 in a 1,000 heavier than unity, so that apparently the electron and proton, when in the form of hydrogen, are this much heavier than when forming part of other atoms. Later on, when referring to the structure of the atom, we shall have occasion to refer again to this curious exception.

CHAPTER V

THE WEIGHTS AND SIZES OF ATOMS

So far there has been little to show what the size or weight of an individual atom must be. All that it has been necessary to suppose is that they are very small compared with any manageable quantity of matter. The atomic weights of which we have been talking are all relative. They tell us merely by how much one atom is heavier than another, but give us no hint as to how many go to say the pound. To find this out we must go back to electrical considerations. Faraday's experiments showed how much electricity was carried by a weighed amount of any element deposited in electrolysis, but on the theory of the last chapter each atom of the substance in the solution has an excess of positive over negative, or of negative over positive, represented by the presence or absence of one or more electrons, the number repre-

senting the valency. This last being known chemically, we have only to divide the amount of electricity required to carry 1 lb. of the element by the charge on an electron and by the valency, to find the number of atoms contained in the pound. Thus the problem of the determination of the weight of an atom is reduced to the determination of the charge of an electron. This charge is commonly denoted by the letter "e." It was stated in the last chapter that this determination had been made, but we will now describe, not J. J. Thomson's original method, but the much more accurate one that has since been used by the American physicist, Dr. Millikan.

The method consists in forming a very fine spray of oil, so fine that the little drops fall very slowly in air, so slowly, in fact, that they can be viewed in a microscope and timed with a stop-watch as they fall from one spider line to another in the field of view. If any free electrons or other gaseous ions are present in the air through which these drops are falling, every now and then one of them will come in contact with the drop and cling to it, so that the drop becomes charged. Such free electrons can be produced by passing X-rays

through the air. Now when the drop is charged it is subject to electric action, and if the whole process takes place between two metal plates the motion of the drop can be modified as desired by electrifying the plates. Instead of falling, it may be pulled upwards by the electric force. If the electricity is switched off the drop will fall again, and the

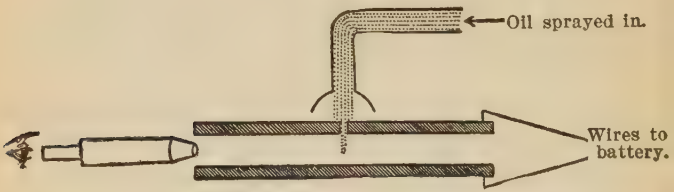

Fig. 6.—Millikan's Apparatus for Finding the Electronic Charge.

process of rise and fall may be repeated many times.

Millikan was able in this way to play a kind of cup and ball with his oil drops sometimes following the same drop moving up and down over about $\frac{1}{20}$ of an inch for an hour at a time. Now the rate of fall of a drop will depend upon its size, as is familiar in the case of rain. The large raindrops fall fast while the very minute drops, which we call mist, fall so slowly that their downward motion is

obscured by chance currents of air. Hence by timing his drop when it was uncharged Millikan could tell its size and weight. Now take a simple case. Suppose that when the electricity was applied the drop moved up as fast as before it had moved down. Then clearly the electric force upon it was twice its weight, once to balance the weight and once to give it the same motion upwards that the weight had given it downwards. Now the degree of electrification of the plates could be measured, and hence the charge on the drop could be calculated.

But we may ask, how could one be sure that the charge really was an electron? The answer is that it was indeed not always one, but that the very variation was perhaps the strongest proof that had yet been obtained of the electron theory. For Millikan found that the speed of the drop in the electric field underwent sudden changes, sometimes in one way and sometimes another, but that the changes in velocity were always the same, and thus could be accounted for by supposing that the particles lost or gained a unit charge. From the change in speed the magnitude of this charge could be found, and the total

charge on the drop was found to be always an exact multiple of this unit. The jerky changes of charge by the same definite unit each time are surely most conclusive evidence that electricity is not continuous but is divided into small units. The value which Millikan found, $e = 4.77 \times 10^{-10}$ electrostatic units probably does not convey much to any but the professional physicist. However, the deduced value of the weight of a hydrogen atom, from which that of any other atom can easily be found, shows clearly the extreme minuteness of the scale on which the universe is constructed. The weight in grammes is 1.65×10^{-24}. This figure means that eighty thousand million million million even of the heavy lead atoms would be required to form an ounce. Put in another way, the weight of a hydrogen atom bears about the same relation to a small shot that the weight of a man does to that of the whole earth. Or again, the smallest particle that can be clearly seen in a microscope would probably contain a number of atoms greater than the population of the earth.

Once the weight of an atom is known, it is easy to arrive at some sort of an idea of its

size, because the great resistance to compression shown by solids and liquids suggests that the atoms in these cases are probably nearly or quite in contact. Knowing, for example, the number of atoms in 1 oz. of lead and the volume occupied by the ounce, we can deduce the average space occupied by each atom, but of course this would not give a very exact value, because we have no right to assume that the atoms take up all the space. For example, a bag of marbles may be full in the sense that no more can be forced in, and yet there is bound to be a considerable amount of empty space in the interstices between the marbles. However, making the rough calculation on the lines indicated it is found that most atoms have a diameter of about $\frac{1}{100}$ millionth of an inch. In order to find the exact sizes it is necessary to know how the atoms are arranged in particular substances, for only thus can we tell how much of the volume of a given substance is actually occupied by them, and how much represents the spaces between the marbles on our analogy. This has been made possible by the use of X-rays, whose short wave-length enables them to be used as a kind of light to "see" the

relative positions of the atoms. This could not be done with ordinary light, for it can be proved that there is a natural limit to the power of a microscope in virtue of which objects can only be distinguished separately if they are further apart than about half a wave-length. For ordinary light this is about a thousand times the size of an atom. For X-rays it is appreciably less than atomic dimensions.

CHAPTER VI

THE ARRANGEMENT OF ATOMS IN CRYSTALS

We have seen (p. 45) how the fact that the atoms in a crystal are arranged in a regular pattern can be made use of to measure the wave-length of X-rays. Conversely, it is possible to use X-rays of known wave-length to investigate the arrangement of the atoms in a particular crystal. We have compared the atoms in a crystal to soldiers drawn up in close order, and this regularity of arrangement shows itself in the regularities of outward form which first attracted the attention of naturalists and chemists to these bodies. If one examines a crystal of fair size, whether it be a natural one such as a piece of rock crystal (quartz), or one made artificially such as one of washing soda, the first thing that strikes one is that the crystal is made of a number of flat surfaces meeting along straight lines. If one examines a number of specimens of crystals of the same

substance, one sees a general resemblance between them, but not apparently an exact similarity. For example, crystals of quartz may be long and thin or short and stumpy, but they are nearly always six-sided prisms capped with a point made of a number of facets. The careful measurements of crystallographers have proved that every face of a crystal can be assigned certain numbers which describe its position, and that the angle between any pair of faces described by the same numbers is the same for all crystals of the same substance however grown. The meaning of this law can best be seen by considering a very simple model in two dimensions. Imagine a number of atoms arranged in a simple square pattern as shown, and thus constituting a kind of crystal. The possible faces are planes (or rather *lines* since our atoms are arranged on the flat and not in space), which pass through a number of atoms. Some of the simplest are shown by the dotted lines in Fig. 7. Now a real crystal would be represented by a region like ABCD bounded entirely by possible faces. If one face is shifted parallel to itself, e.g. AD to A′D′, a considerable change is made in the appearance of the crystal, but from the

crystallographer's point of view this is quite a secondary matter, the important thing being that all the angles of A′BCD′ are the same as those of ABCD. The business of the crystallographer is to find and measure all the faces

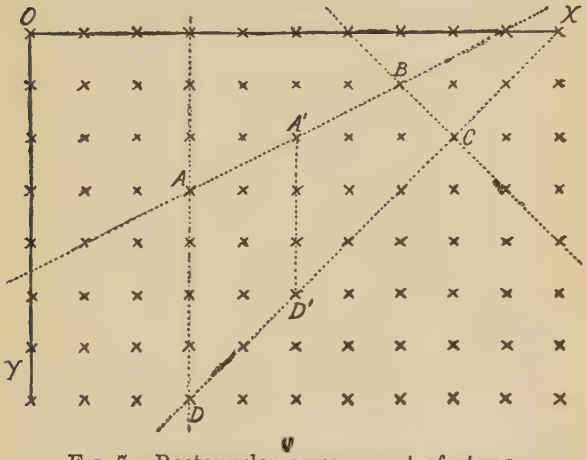

Fig. 7.—Rectangular arrangement of atoms.

which ever occur in a crystal of a given kind, and find some simple way of expressing their directions. The way that is used depends on what are called the Axes of the crystal. These are certain directions in the crystal which correspond to some specially simple regular-

ities in the arrangement of the atoms. For example, OX, OY, in the Fig. 7. They are not necessarily at right angles, e.g. Fig. 8, and in certain cases there may be more than one set which would do equally well. When suitable axes have been found, every possible face can be described by the relative number of

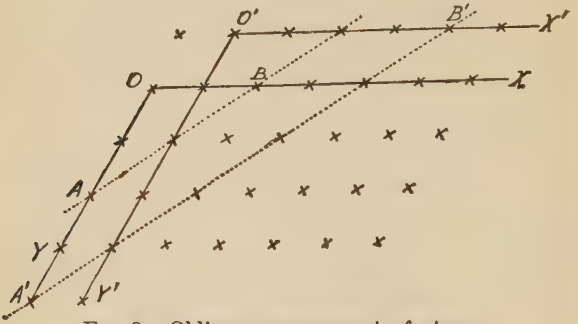

Fig. 8.—Oblique arrangement of atoms.

steps from O at which it cuts the axes. Thus for the face AB (Fig. 8) the numbers are equal, 2 on each. Notice that the numbers are also equal if the axes are drawn as O′X′, O′Y′, or if the face is drawn as A′B′. In all cases it is only *directions* which matter. For real crystals three axes have to be taken corresponding to the three dimensions of space. The faces

are denoted by "indices" which are the number of planes in the series parallel to them which would go through unit space on each axis. Thus the planes drawn in Fig. 9 have index 2 for the X axis and index 1 for the Y

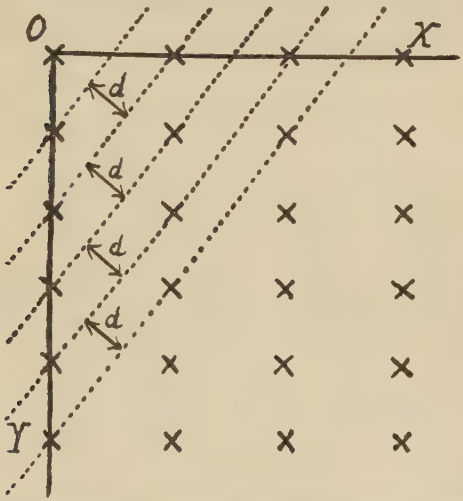

FIG. 9.—Dotted lines show a set of crystal "planes."

axis. The spaces may be different for the different axes.

So far we have thought of the crosses in the diagrams as meaning individual atoms. In the case of compounds the atoms will be of different kinds, but in *all* cases there is a

definite *group* of atoms, which may or may not be the ordinary chemical molecule, which acts as a unit in the pattern. The pattern can be made up by endless repetition of this elementary group, each group being placed exactly parallel to its neighbours and at constant distances from them, very much like the

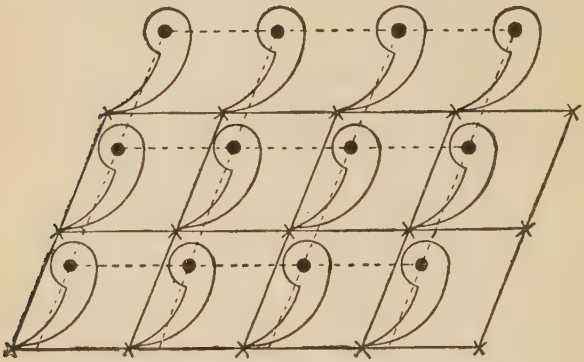

Fig. 10.

pattern on a wall paper. In Fig. 10 this is illustrated by the repetition of the comma-shaped objects. Now if we take the *same* point of each group we shall get an arrangement of points like those we had before, nor does it matter which particular point of the group is taken. This is illustrated in Fig. 10,

where the patterns of the crosses and circles are clearly identical except for a bodily shift. The pattern formed in this way by representative points of the various groups of a solid crystal is called a "space lattice."

Crystals possess varying degrees of symmetry, which shows itself as a regular repetition of the faces. Take, for example, an ideal crystal in the form of a cube. It possesses a number of kinds of symmetry. For example, take a line through the middle of one face at right angles to the face. If the cube is turned about this line, it will occupy its original position four times in a revolution. This is called an axis of fourfold symmetry. Again, each line joining a pair of opposite corners of the cube is an axis of threefold symmetry. There are also a number of planes of symmetry, such that if they were mirrors, the reflection of one half of the cube would coincide with the other half (Fig. 11). An actual crystal may have more symmetry than appears from its outward shape; thus a crystal which, so to speak, ought to have been a cube, may have been distorted because its growth in certain directions has been interfered with. In consequence the sides of the cube may have grown

of unequal lengths; but unless the distortion has been so great as to prevent the formation of the faces altogether, the *angles* will be unchanged and the symmetry of the ideal undistorted crystal can be restored in imagination. This symmetry is a consequence of the sym-

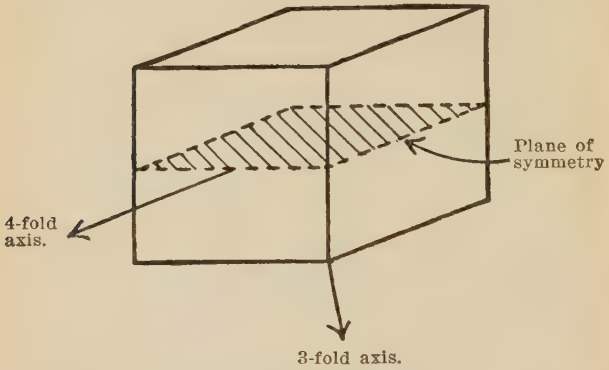

Fig. 11.—Cubic symmetry.

metry of the atomic arrangements. Thus the space lattice of Fig. 7 is such that if the whole pattern is turned about one of the crosses, it will coincide with its original position four times in a revolution. In the case of Fig. 8 and Fig. 9 it will only coincide twice. Again, in Figs. 7 and 9 if the pattern is folded across any line parallel to OX or OY joining the

crosses, the part folded over will coincide with the rest, but this is not true for Fig. 8. One can see, then, how from the observed symmetry of the finished crystal one can deduce a good deal as to the arrangement of the groups. Something can even be deduced as to the structure of the groups. Thus, to take a case in two dimensions, if the molecule were entirely unsymmetrical, represented by a comma, and the system showed a fourfold axis of symmetry, not merely must the space lattice show this symmetry, but the group which fills the lattice cell must show it also. One way in which such a symmetrical group can be built out of unsymmetrical pieces is shown, arranged in a lattice, in Fig. 12. Notice that two kinds of objects, commas, have to be used which differ as the print of a right foot differs from that of the left.

In three dimensions the same kind of argument applies, but the problem is more complicated and the possibilities more numerous. However the reader may be prepared to believe that in the case of crystals which show a high degree of symmetry and whose molecules are fairly simple, there are not many possible alternative arrangements of the atoms which

would give the observed symmetry. Nevertheless, until the discovery of the diffraction of X-rays by crystals, it was not possible to

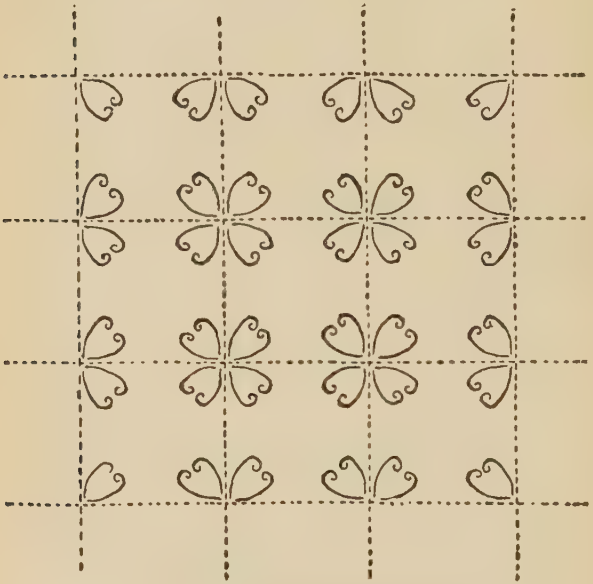

Fig. 12.—Lattice of symmetrical groups.

fix definitely the arrangement of the atoms in even the simplest crystal.

The principle of X-ray diffraction is an extension of that of the diffraction of light waves

by a grating of slits. If light of a single wave-length is transmitted through a glass plate ruled with a number of fine lines close together, a number of beams are formed. One consists of the light which goes straight through without deviation; this is unimportant for our purpose. On each side of this are a series of beams at definite angles of which the nearest are usually the strongest, and will alone be considered. Thus taking the light deviated to one side only, there is one strong beam, but the angle at which this beam comes off depends on the wave-length, so that if several wave-lengths were present in the original light there would be beams in several directions. This group of beams constitutes the spectrum of the light formed by the grating. This is what happens when the ruling on the glass forms a single series of scratches regularly spaced, as is normally the case in practice (Fig. 13*a*) (the scratches are practically equivalent to a series of opaque obstacles on the glass). But if we made a grating with *two* regular spacings (Fig. 13*b*) we should find that the beam corresponding to each wave-length was doubled, and we should get two spectra superposed. This of course would be an inconvenient complication,

and nobody would deliberately make a grating like this, though such effects do sometimes occur as the results of accidental errors in the ruling. In a crystal we can't help it happening as we have to take what nature provides, and

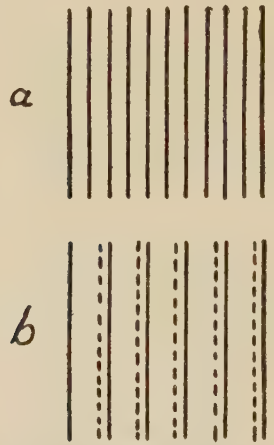

Fig. 13.—Single and double spacings.

though it may be an inconvenience from the point of view of investigating the X-rays it is of great value when we want to find the crystal structure. The principle is that every regular spacing gives its own spectrum. For a crystal the "regular spacing" in question is

that between successive pairs of planes all drawn parallel to the same crystal face through successive points of the space lattice. Such a spacing is marked "d" in Fig. 9. Since there are many possible crystal faces there are many spectra. Also since the X-rays penetrate the crystal it is not necessary for the face to have been actually formed at the surface. The regularity of structure exists, though the face may have broken away, or never even formed because it had been crowded out by the growth of adjacent faces. Indeed, since some of the crystal faces grow much more readily than others, many possible faces are rarely or never found in practice, but the corresponding regularities can be detected by X-rays. For example, in the diamond, which is crystalline carbon, the natural crystals are rounded, owing either to the surface having been ground away or to the interference of the surrounding material with the process of crystallization when the diamond was formed. The facets artificially cut on gems do not necessarily correspond to any possible natural faces.

There is one important distinction between a crystal and a plane grating with many spacings. The latter would give all its spectra

simultaneously, the former only gives a spectrum with a particular wave-length if it is held at the proper angle. This difference is caused by the fundamental difference between a three-dimensional arrangement of atoms, and a spacing of parallel lines on a plane. It is a fortunate one for the investigator of crystals, for it saves him the confusion which would occur if all the spectra appeared simultaneously. On the other hand, he has to provide his apparatus with some device for rotating his crystal in all directions, so as to place it at the proper angles to the rays to give the spectral lines.

When this work was first begun, neither the wave-length of the X-rays nor the arrangement of the atoms was known. The first step is to find the arrangement in *one* crystal, then this can be used to measure wave-lengths, and with the wave-lengths known more complicated crystals can be attempted. After the original discovery by Laue of the existence of X-ray spectra, Professor W. L. Bragg succeeded in solving the first problem using common salt, of which large crystals occur in nature as rock salt. This is a simple compound in which one atom of sodium combines with one of chlorine, and the crystals are highly

symmetrical. The alternative arrangements can be restricted to a few possibilities by arguments on the lines of those we have just been considering. Further progress can be made by using the X-ray spectra. It will be remembered that the deviation of a beam depends on the relation between its wave-length and the spacing of the grating, in this case, of the crystal. Thus even if the actual wave-length is unknown, the position of the beams formed by the different spacings in the crystal gives their relative values. In this way the possibilities can be still further restricted. Finally the *intensity* of the different beams depends on the distribution of the atoms in a way which can be calculated roughly, so that the observed effects can be compared with those to be expected on various possible arrangements. Now potassium chloride forms crystals very like those of sodium chloride, and the close chemical similarity made it practically certain that the atoms were arranged in the same way in the two crystals, except for the exchange of one atom of potassium for each atom of sodium. A comparison of the intensities for the two crystals made it possible to settle the structure of each.

Once the arrangement is known the distance apart of the atoms was easily found as follows. A certain typical cube in the structure contains 4 atoms of sodium and 4 of chlorine. The weights of these are known, and we have only to find what sized cube of common salt would have their weight; this is easily done since the weight of a block of a centimeter cube can be found directly. From this typical dimension the distance between the centres of the atoms can be found from the geometry of the arrangement.

Knowing then any typical spacing and the position of the corresponding beam, the wavelength of the X-rays used to form it can be found. The results lead Moseley to the classification of the atoms in their natural order as described on page 46. For the purposes of further work on crystals, known X-rays are used and the different typical spacings can be determined. With these and the symmetry as guides, considerable progress can be made in unravelling the atomic arrangements of other crystals. But except in the simplest cases there are still many possibilities which can only be distinguished by measuring the intensities of the spectra.

Investigations of this kind are, moreover, by no means easy, for besides the difficulties which most people always find when it is necessary to think in the solid, there is apparently no way of constructing an infallible machine which will work back from the observed intensities of spectra to the arrangement of atoms which causes them. Thus the process is necessarily a tentative one, and practically amounts to trying probable arrangements of atoms until one is found which will fit. In spite of these difficulties, the structure of a large number of crystals has been solved largely as the result of the work of Sir William Bragg and his son, W. L. Bragg. One discovery has been of great help in this work; namely, that in many cases at least the crystals can be regarded as built up of spheres representing the different atoms and touching one another, the sizes of these spheres being characteristic of the different atoms. Thus if, for example, the positions of some of the bigger atoms can be fixed, it is often found that there are only a limited number of places where room can be found for the others. The process is a little like the last stages of a jig-saw puzzle when

it becomes obvious that only in a few places is there room for a particular piece. This discovery is equivalent to assigning definite sizes to the atoms, and shows that they can be regarded, at least approximately, as spheres. These sizes are not quite exact in the sense that slight variations have to be assumed to fit different crystals, but the variations are not more than might reasonably be expected as a consequence of the distortions caused by the forces between the atoms. The fact that one can build up crystals out of atoms, like making piles of cannon-balls, makes the atoms seem extremely real and vivid. The sizes of the atoms, found in this way, small though they are, are almost as directly measured as if it were actually possible to measure their sizes under the microscope. The diameters of most atoms found in this way are round about a hundred-millionth of an inch. Though sizes vary, there is much less variation in size than in weight, few atoms being so small as half this diameter or so large as twice it. As a comparison it may be remarked that the most accurate fitting carried out in engineering is about $\frac{1}{10000}$ of an inch, which would thus correspond to a

thickness of 10,000 atoms. It is, however, possible to prepare metallic films only about thirty atoms thick which will hold together and reflect light.

CHAPTER VII

RADIO-ACTIVITY

The two or three years following the discovery of X-rays at the end of 1895 probably brought forth a larger number of discoveries of the first importance in physics than any equal period before or since. Besides the work on X-rays this period covers the determination of the charge and mass of an electron, the foundation of the study of the conduction of electricity through gases, and the fundamental experiments of what is now almost a science in itself, Radio-Activity. The starting-point was the discovery by the French physicist Becquerel that uranium emitted a type of radiation capable of affecting a photographic plate. This was the outcome of a search for new types of radiation stimulated by the discovery of X-rays.

It was soon found that besides their photographic action the rays from uranium, like

X-rays, had the power of making air conducting. This property being more amenable to quantitative measurement was that chiefly used in the further developments. The most important of these came from the work of Professor and Mme. Curie, who found that it was possible to separate from the uranium by chemical means other substances which, weight for weight, were much more active than the original uranium. The first of these was named Polonium in honour of Mme. Curie's native country. The second is now world famous under the name of Radium. Though they constitute only a negligibly small proportion by weight of the uranium in which they are found, they contribute a considerable proportion of the whole activity.

The leading principle which guided the Curies in this work was that radio-active effects were essentially atomic. It made no difference how, for example, the uranium was combined. The activity for the same number of atoms was always the same, nor could it be altered by changes in physical condition such as heating or dissolving the uranium compound in water. Enough of the radium was extracted to make it possible to study its

chemical properties, and it was found to be an element belonging to a well-known group in the periodic table and similar in its properties to the metal calcium, which forms the basis of the familiar chalk and limestone. There was nothing in its chemical properties to lead one to suppose it capable of producing these remarkable physical effects, its only peculiarity being that, like uranium, it had a very large atomic weight. Uranium, indeed, is the heaviest of the elements, and radium comes not far behind. Other radio-active substances were discovered soon after, among them Thorium, one of the substances used in making gas mantles, and the element with the second heaviest atom then known.

The radiations from uranium in its natural state are not all of the same kind. Three types were distinguished as Alpha-, Beta- and Gamma-Rays,[1] this being the order of their penetrating power. The alpha-rays can only pass through two or three inches of air and are stopped by all but the very thinnest layers

[1] These "rays" were named before their nature was certain. As will be seen from what follows, only the last belongs to the class of light or ether radiations and has a place in the spectrum. The others are charged particles.

of solids; the beta-rays can pass through thin sheets of aluminium; while the gamma-rays can penetrate a considerable thickness of lead. The further investigation of these radiations, and of the connection between the various radio-active elements is largely due to the work of Rutherford and his collaborators.

Rutherford and Professor Soddy advanced the startling view that radio-activity was a process of spontaneous change from one type of atom to another. The revolutionary nature of this idea may be appreciated when it is remembered that for a hundred years since the days of Dalton, if not earlier, scientists had been inclined to regard the atoms of chemical elements as indestructible and immutable. Much more or less good-natured contempt had been poured upon the attempts of the mediæval alchemists to transform one type of element into another. It is true that J. J. Thomson had shown that electrons could be broken off from the atoms which contained them, and so had destroyed the idea of the atom as an indestructible entity. But the parts so removed are a very small portion of the atom, and what is more important, the rest of the atom preserves its chemical in-

dividuality and reverts to its normal state as soon as it can find another electron to join it. The change in radio-activity, on the other hand, is a permanent one, and the chemical properties of the resultant atom are totally different from those of its parent. It would take too long to describe the methods by which were unravelled the relations of the long chains of radio-active substances now known to exist, but the main results are these. An atom of a radio-active substance may be likened to a loaded gun which sooner or later goes off, how or why are still complete mysteries. The bullet represents the ray, which in the majority of cases is either of the alpha or beta type. The rest of the gun forms an atom somewhat lighter than the original, and of quite different chemical properties, but this new atom in its turn is generally radio-active and goes off again ejecting a particle, not necessarily of the same kind as the first. The process goes on perhaps a dozen times, the final product being an atom of lead. There are three such series known, one starting from uranium, one from thorium, and another called the actinium series, which probably arises as a kind of by-product at one stage of

the transformation of uranium. Thus every radio-active substance is continually breaking down into something else, and being replenished by the breakdown of something higher in the series. All, that is, with the exception of uranium and thorium, which have nothing to replenish them.

The average life of the radio-active substances varies enormously, from less than $\frac{1}{1000}$ of a second to thousands of millions of years. Times of almost every intermediate order of magnitude are represented; thus we have substances with lives of a few seconds, minutes, days, years and longer epochs. Uranium itself has the longest of all, so that even during the lifetime of the earth the amount of uranium on it has probably not greatly diminished. Thus, if we think of the descent of radio-active substances as a kind of genealogical tree, the generations are of very unequal length. But there is another very fundamental difference between the life of a radio-active atom and of a man. In a human population the chances of death depend enormously on the age of the individual; if he survives a dangerous period in the first year or two of his life, he is likely to live to

fifty or sixty. The death-rate among octogenarians is very much greater than among men in the twenties. But with atoms this is not so. If they are subject to death they at least have the secret of perpetual youth. The atoms of a radio-active gas known as Radon have an average life of five and a half days, but the survivors after five days are just as likely to live another five days as an atom of the same kind that has just been born. Those of them who survive their extra five days are as likely, or as unlikely, to live another five, ten or twenty days as a newly born atom. The death of an atom, in fact, appears to be pure chance and not the result of the running down of some mechanism inside the atom, as is the process which will ultimately cause the death of a man or animal from old age even if he has survived the vicissitudes of accident and disease.

Chance is in truth only another name for ignorance of the causes, so perhaps we shall not always be obliged to describe radio-active change in this way. Nevertheless questions involving chance and the allied idea of probability seem to be playing an increasing rôle in physics, and there is an important school of

thought which regards them as representing, in some cases at least, a limit to the possibility of knowledge.

We must now turn from a consideration of the gun to that of the projectiles. The alpha particle was shown by Rutherford in the course of the brilliant research which first established conclusively the transformation of atoms, to be itself an atom stripped of two electrons. When it regains these two, as it does near the end of its path, it becomes an atom of an inert gas helium which was first discovered in the sun from its spectrum, and afterwards found in some of the natural gases emitted from the earth. It is a light atom weighing only four times as much as one of hydrogen. The speed with which an alpha-ray is shot out is very great, and the effect is so vigorous that it is actually possible to detect a single one. If a screen is prepared coated with a thin layer of certain minerals (zinc sulphide is the best) and a small amount of radium placed near it, the screen glows brilliantly. If the amount of radium is reduced so that an alpha-ray only reaches the screen once every few seconds, and if the screen is viewed through a suitable microscope, an observer whose eyes have been

carefully rested by a long period in the dark sees, not a constant illumination, but an occasional feeble flash. This flash represents the arrival of an alpha particle at the screen. Thus by a process of simple counting we can find how many alpha-rays the source of radium sends out. By comparison of the electrical effect of this feeble source with that of a stronger one we can deduce the number of alpha particles which would be given out per second by a weighable quantity of radium. If the alpha particles from this larger source are fired into some vessel where they can be collected they will accumulate there as helium. After a considerable time enough helium will be collected to give a measurable volume, and thus by the direct process of counting a few and multiplying up, the number of atoms in a measured quantity of the gas can be determined. The results are in excellent agreement with the values found from the weights of the atoms calculated by the method explained in the earlier chapter, and form a magnificent confirmation of the theory.

The directness of this method of counting (sometimes called the scintillation method) is one of the clearest pieces of evidence for the

reality of atoms. When, as is the case now, the conceptions of physics are being closely scrutinized from a philosophical point of view, such a direct piece of evidence is extremely valuable. It is true that we do not here actually see the atom. Strictly speaking, we see only the light caused by its impact; but it would be as reasonable for an observer on a battleship at the Battle of Jutland to refuse to believe in the reality of German shells because no piece of one actually hit him, though he had seen the splashes they threw around him, as to disbelieve in the reality of atoms after this experiment.

In contrast to the alpha-ray, the beta-ray is an old friend. It turns out, in fact, to be nothing more or less than an electron, going it is true somewhat faster than is usual in the cathode-rays. Curiously enough this difference in speed, though apparently of secondary importance, has in fact brought out a very important point. It is found that among the faster beta-rays whose speed is not far short of that of light, the mass is appreciably larger than the mass of an ordinary electron. It takes, that is to say, a greater force to bend a beta-ray of this high speed than one

would have expected from experiments on the cathode rays. Elaborate experiments have been made to measure this effect and to find the mathematical relation which connects the mass with the speed. A comparatively simple expression was found to give the best agreement. It makes the mass hardly vary until the speed becomes a considerable fraction of that of light. But when the mass begins to increase it does so at a rapidly increasing rate, so that, if the theory held, the mass actually at the speed of light would become infinite. Actually beta-rays are known with a speed only 2 or 3 per cent. less than that of light. For such an electron the mass is four or five times greater than the normal.

The greatest interest of this result is that it is one of the most important confirmations of the theory of Relativity. As is well known, this theory predicts that no material object can travel faster than light. This must be so if the mass increases without limit as the speed of light is approached, for an indefinitely increasing force will be required to accelerate it as it approaches this limit, and no finite force can ever make it exceed it. Relativity, in fact, predicts a mathematical relation be-

tween mass and speed which is precisely that found for the beta-ray in these experiments. Not all the beta-rays, however, have velocities approaching this, and the velocities of the slowest are not greater than those of fast cathode-rays.

The gamma-rays only differ from X-rays in their method of production and in being usually, though not always, of shorter wave-length than the X-rays that are commonly produced artificially. They appear to be for the most part a secondary consequence of the emission of beta-rays. The radio-active atom, in fact, acts as an X-ray tube in miniature, the beta-rays causing the gamma-rays, as the cathode-rays cause the X-rays. Only one particle, be it an alpha- or a beta-ray, is primarily released in each atomic disintegration, but sometimes other slower electrons are emitted by a secondary process.

CHAPTER VIII

SOME CONSEQUENCES OF RADIATION AND COLLISIONS

It has already been stated that X-rays and the rays from radio-active substances have the power of making a gas through which they pass a conductor of electricity. In the following chapter we will examine the mechanism of this process. The above agents all produce the effect in the same general way, namely, by removing one or more electrons from some of the molecules of a gas, leaving these molecules with a positive charge. The electrons may remain free, or may attach themselves to other molecules of the gas, giving them a negative charge. It must be kept in mind that, since by convention the charge of an electron is negative electricity, a negatively charged molecule is one with an extra electron, while a positive charge implies deficiency of electrons. Protons can only be detached

from an atom under very abnormal conditions to which reference will be made later. The charged molecules move under the influence of electric forces, and their motion constitutes the current in the gas. The process is very like that of conduction in liquids, with the important difference that in the gas the charged molecules, or ions as they are called, have to be produced by some external cause. If after exposure to X-rays the gas is left to itself the positive and negative charges attract each other, and when the molecules carrying them come together the electron is transferred from the molecule which carries it, to a molecule which is an electron short, thus reforming two ordinary molecules. The power of conduction will then cease and the gas relapses into its ordinary condition. In a liquid, on the other hand, the ions are produced spontaneously.

While a good deal was found out by various indirect methods of the way in which ionization is produced, there is one type of experiment which shows the process so clearly and vividly that it is not worth spending time in describing the older methods. The experiment referred to is due to Professor C. T. R.

Wilson, and, like so many discoveries, had its first germ in the year following the discovery of X-rays. It depends on a process which at first sight has extremely little to do with atomic physics, namely the production of rain or mist. It is well known that when ordinary air, which always contains a certain amount of water in the form of invisible vapour, is sufficiently cooled the water is deposited in the form of drops. If this happens near the surface of the earth, we call it a mist; if higher up, a cloud. Now experiments made nearly fifty years ago in the artificial production of mist had shown a strong tendency for the water to condense on small particles of dust. It may be shown from arguments based on the theory of heat that it is very difficult indeed for a drop to form unless it has some centre on which to collect. In the ordinary way the dust particles in the air supply these centres, and the clearness of the air after rain is largely due to the fact that the dust has been used up in this way and fallen to the ground in the centres of the rain-drops. But Wilson showed that even in air that had been carefully filtered free of dust, condensation could still occur to a slight

extent, and that the number of drops was vastly increased by subjecting the air to X-rays or other ionizing agents. He concluded that the centres of these drops were the ions, a few of which are always present in the air, owing chiefly to minute traces of radioactive substances on the earth. The method thus affords a means of determining the number of the ions present in the air, and was in fact the basis of J. J. Thomson's original method of measuring the charge of the electron. We are now concerned, however, with a quite different application.

The cooling is produced in a cylindrical glass vessel containing moist air, the bottom of which can slide as a piston. If this piston is suddenly pulled down the air expands and cools. This effect is the converse of the well-known fact that compressing air, for example, in a bicycle pump, produces heat. The expansion is so adjusted that drops form on all the ions present, and the source of ionization is made sufficiently feeble so that the drops are not so numerous as to be confusing. It is found that the drops show arrangements characteristic of the way in which the ionization has been caused. Take first the case

which shows the simplest pattern; if the gas has been ionized by a minute speck of a substance which gives alpha-rays, radium itself for example, one sees a number of straight lines diverging from the speck, each made of drops so close together as to give the appear-

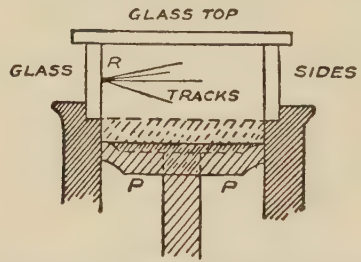

FIG. 14.—Section of the Expansion Chamber in Mr. C. T. R. Wilson's apparatus for measuring the track of Helium Atoms.

The Piston PP is dropped suddenly from the position indicated by the dotted lines to the position indicated by the full lines; so that the air in the expansion chamber is suddenly chilled by the expansion, and fog settles on the tracks of the Helium Atoms shot out by the radium at R.

(*From Sir William Bragg, "Concerning the Nature of Things"; G. Bell & Sons, 1927. By kind permission of the Cambridge Scientific Instrument Co.*)

ance of continuity. Sometimes the lines show slight angles, and sometimes, but very rarely, they fork into two. These lines of drops are often spoken of as "tracks," and each one of them shows the path which an alpha particle

has made in going through the air, producing ions all along its course. A photograph of these tracks is one of the most convincing proofs of the reality of individual particles in the rays. The rays must be regarded as producing ionization by the brute force of their impact, which bores its way through the molecules knocking out some of the electrons with which it happens to come into particularly close collision. This process is called ionization by collision.

If instead of a source giving alpha-rays we choose one of beta-rays we still get a series of tracks, but there is a characteristic difference which enables them to be distinguished at a glance from those furnished by the alpha-rays. The beta-ray tracks show gradual curves and are often twisted right round before they come to an end. The number of ions produced in a given distance in each track is also less, so that the drops are less dense and the track has often more the appearance of a series of dots. Indeed, with suitable magnification and choice of conditions it is possible to see separately the individual ions that are formed, which as might be expected occur together in pairs. Sometimes also little groups

of ions, and even short tracks, occur detached from the main ones.

If the ionization is produced by a beam of X-rays the appearance is totally different. If the expansion chamber is shielded by lead blocks so that the rays only go through a part of it, this portion shows, after the expansion, as an intricate tangle of short curves looking rather like a pathway thickly littered with bits of straw. Each of the separate little curved tracks closely recalls that of a beta-ray in miniature. It is now known that they are, in fact, the tracks of electrons ejected by the X-rays with speeds very fast indeed by ordinary standards, but slow compared with the beta-rays, and comparable with those of ordinary cathode-rays. Thus X-ray ionization is a double process. First a few fast electrons are thrown out, and then these in their passage through other molecules of the gas produce ions by collision with them. Thus the ionized region will spread sideways some distance beyond the limits of the original X-ray beam. It is found that the greatest velocity of these fast electrons is determined by the wavelength of the X-rays; the shorter the wavelength the greater the maximum of velocity.

Now a similar rule holds in the original production of X-rays. These as will be remembered are formed when the cathode-rays strike an obstacle, and the faster the cathode-rays the shorter in general is the wave-length of the X-rays produced. The connection is more than merely qualitative, for the fastest electrons ejected by the X-rays are found to have a speed indistinguishable from that of the electrons to which the X-rays were originally due. Though only a few of the electrons are as fast as this, most of them have speeds quite comparable and as we shall see later on this is an instance of one of the most far-reaching laws of modern physics.

The Wilson method of investigation is only suited to the study of ionization by fast and therefore penetrating electrons. But electrons continue to ionize by collision down to relatively slow speeds of the order of $\frac{1}{100}$ of a fast beta-ray. The study of this kind of ionization has been carried out in a type of apparatus very similar to a wireless triode valve. Indeed, some of the early valves contained gas at a low pressure and made use of the effect. In this case the electrons are produced from the heated filament which lets

them escape into the space round it like steam from boiling water. They are then driven through the gas by a high-tension battery. Ionization can be detected by charges in the currents between the grid and plate. It is found that ionization only occurs when the electrons exceed a certain speed which differs somewhat for different gases. For air it is about that which the electron acquires when accelerated by a battery giving 16 volts. An important fact is that light is produced in the gas by electrons of a smaller velocity, but here too there is a definite lower limit. Nothing happens until this is reached. It is as though an atom could be cracked by electrons, hitting it with more than a certain speed, and could be broken if the speed were somewhat greater. The analogy can be followed out to the extent that it has been shown that the "cracked" atom, i.e. one emitting light, can be broken (ionized) by a smaller velocity than a whole one. But unlike a piece of crockery the atom has the power of mending itself, and returns to its normal state when it has finished emitting the light.

The critical speeds above which the emission of light and ionization occur are of great

importance in the study of the structure of atoms, and we shall have occasion to refer to these quantities again in that connection. They are generally measured in terms of the voltage required to accelerate the electrons up to the speed in question. The value for ionization is called the Ionization Potential of the substance, and that for the emission of light the Resonance Potential.

CHAPTER IX

UNITS OF ENERGY

PERHAPS no development of modern physics has been so entirely unexpected and surprising, even to those who have produced it, as the discovery that energy, like matter and electricity, exists in definite units. This discovery has coloured the whole progress of physics in the last twenty years, and the group of conceptions and ideas derived from it are often spoken of as the Quantum Theory, though until the last two or three years there has been nothing which could really be described as a logical and self-consistent theory. Rather has there been a group of empirical results which seemed in some mysterious way to be connected together. It is the purpose of this chapter to explain in outline some of these facts, and to show the connection underlining their apparent dissimilarity.

First in historical order came the study of the radiation produced by what is technically called a constant temperature enclosure. By this is meant an enclosed furnace, the walls of which are all at the same temperature. To study the radiation which this emits it is necessary, of course, to have a small hole somewhere to let out a sample, but this can be made small enough to have no appreciable effect on the conditions. Apart from the importance of such radiations as a practical means of measuring furnace temperature, for which they are frequently used, their great interest lies in the fact that, as is shown both by theory and experiment, they are independent of the materials of which the furnace is made. They have therefore the peculiarity of being a phenomenon caused by matter, but one which is independent of the particular kind of matter used. This suggests that they represent something fundamental in the scheme of things. Such radiations show a continuous spectrum, but not all parts of the spectrum are equally bright. There is one wave-length, or rather a region of wave-lengths, for which the radiation is most intense, and this wave-length decreases as the

temperature increases. This is really a more precise statement of the familiar fact that the colour of a glowing coal or piece of metal changes with the temperature, the light being first visible as a dull red, and becoming whiter as the temperature increases. The wave-lengths for which the radiation is strongest move from the red or long wave end of the spectrum towards the blue. If it were possible to raise the temperature of the glowing body sufficiently, it would appear of a bluish tinge. Strictly, of course, a single lump of coal does not form an enclosure in the proper sense, but the difference in quality of the radiation is usually not very great.

Now when an attempt was made to explain on mechanical principles this distribution of the energy of the radiation in the spectrum, it was found not merely that the results predicted did not agree numerically, but that they were of a totally different character from what was observed to be actually the case. Thus in theory there should be no predominant wave-length, but at all temperatures almost the whole of the energy of the radiation should be confined to indefinitely short waves. This result can be shown to follow from very gen-

eral mechanical principles if the assumption is made that energy can pass from matter to radiation, and back again, in continuously variable amounts. Up till then this assumption had never been questioned, but Planck in the year 1900 showed that one could reconcile the theory to the experiment, not merely roughly, but with the highest accuracy, if this assumption were denied. He supposed instead that changes of energy from matter to radiation and back again could only take place by definite amounts at a time. These amounts he called "Quanta." It is thus as though energy, at least for certain purposes, partook of the atomic nature of matter and electricity; but there is a curious and very important difference. While all electrons have the same charge and all atoms of any one kind the same mass, the quanta are not all the same. The energy of a quantum, in fact, is proportional to the frequency of the particular kind of radiation whose transformation is being considered. By the frequency is meant the number of vibrations per second which the undulating medium carrying the radiation may be supposed to undergo. It is equal therefore to the velocity of light divided

by the wave-length of radiation. Since one can have radiation of any possible wave-length, one can have quanta of any possible size. Thus the unitary nature of energy is somewhat less complete than that of matter. In the case of energy it is only for a given wave-length that all the units are equal. The sense in which energy is atomic may be illustrated by a simile. Imagine a library containing a large number of copies of one book of each of a large number of authors. Then if the librarian is asked to furnish, say, exactly 2 lbs. of books he will have no difficulty in making it up if he is allowed to pick and choose. But if he is told that all the books are to be by a certain author it probably will not be possible, because that particular author's book might weight, say, 7 oz., so that five would be too many and four too few. It is in this sense that energy occurs in units. If we are restricted as to wave-length then the amount of energy which can be transferred is a multiple of a definite unit, but if there is no restriction of wave-length then the amount transferred can be anything we please.

To represent the actual size of the unit, Planck introduced a quantity universally

represented by "h." The energy of the unit is h times its frequency. "h" is known as Planck's Constant, and its value was found by him from the measurements of the radiation. The value in the usual scientific units is 6.55×10^{-27}, but it will give a better idea of the real magnitude to say that for red light it represents about the energy which would be given to an electron by a potential of 2 volts. It should be noticed that the value of the quantum gets larger the shorter the wavelength, so that for a typical X-ray the corresponding voltage would be about 50,000. It is obviously in a region where the steps by which energy can change are very large, that we are most likely to observe the effects due to them. Thus the differences between what would be expected on the quantum theory and on the older idea of a continuous interchange of energy is most marked in the case of X-rays, and is hardly observable in wavelengths larger than the visible. As long as the evidence for quanta rested only on the difficulty of interpretation of the radiation from a constant temperature enclosure, physicists were very unwilling to admit such a fundamental change in their ideas. But discoveries

on quite other lines came to confirm it. It had been known for some time that a zinc plate emitted electrons under the action of ultra-violet light. This is called the Photo-electric effect and is really quite general. Any substance will emit electrons under the influence of radiation, but the radiation must have a wave-length less than a value which depends on the nature of a substance and is called its "threshold." Now Lenard found the very surprising result that the maximum speed of these electrons did not depend at all upon the intensity of the light. However strong the light, the electrons came off no faster; the only difference was that there were more of them. Now if, as was thought at the time, light is a continuous wave motion, this is very hard to understand. The speed with which waves roll the shingle up a beach certainly depends upon their violence. But Einstein suggested that this was an instance of Planck's quantum relation. He found that the experiments could be explained by supposing that each electron acquired the energy of one quantum of radiation. Among other things this explains the "threshold." The wave-length must be sufficiently short for the

quantum to have enough energy to carry the electron clear of its surroundings, and this implies a minimum wave-length for a given substance. This idea has proved extraordinarily far-reaching and is the explanation of a large group of important experiments. For example, the ionization by X-rays can be regarded as an example of the photo-electric effect. The wave-length of X-rays being very short, the quantum is a very powerful one and the electron is ejected from the atom with great violence, so much so that it can ionize other molecules by collision and produce the secondary ionization discussed in the last chapter.

This is not the end of what can be deduced from Einstein's idea. If radiation can only be produced a quantum at a time, then there must be an amount of energy at least equal to a quantum to produce it. Now X-rays are formed when electrons are suddenly stopped, and since the electrons presumably act independently, an electron can only produce a quantum of X-rays if it has itself an equal or greater amount of energy. Thus if, for example, the electrons in the cathode-rays have acquired energy by being accelerated by

50,000 volts, they can only give rise to X-rays whose quanta correspond to an amount of energy smaller than this. Applying Einstein's relation and the value of h found by Planck, we can calculate the shortest wave-length which the X-rays can have, and it is found that in fact the X-rays are limited to those of wave-lengths greater than that so calculated.

It is the same with the light emitted by atoms which have undergone a collision with an electron of the resonance potential. At the most the atom can only have acquired the full energy of the electron, and this is all, therefore, that is available for the radiation. Dividing the energy by h gives the maximum frequency. In this case, indeed, the light emitted is found by spectrum analysis to have only the one frequency, which agrees within the limit of experiment with that calculated in this way.

The law, then, is a reciprocal one. It serves to determine the radiation produced as the result of impacts by moving electrons, and it also determines the speed with which an electron can be emitted when the radiation, in its turn, is absorbed by some other atom. How peculiar this law seems when stated in

terms of the older view of radiation as waves in a continuous ether, has been strikingly expressed by Sir William Bragg:

"It is as if one dropped a plank into the sea from a height of 100 feet, and found that the spreading ripple was able, after travelling 1,000 miles and becoming infinitesimal in comparison with the original amount, to act upon a wooden ship in such a way that a plank of that ship flew out of its place to a height of 100 feet."

The attempt to reconcile the new view with the old has been perhaps the greatest difficulty in physics during the last ten years. We shall see later on to what extent this difficulty has been overcome.

A most striking characteristic of the quantum conception, and one which serves to show what a very fundamental part it must play in the structure of the universe, is the way in which it appears in apparently quite disconnected phenomena. The one to which we now turn is an abnormality which has been found in the capacity for heat of certain substances at very low temperatures, such as that of liquid air. The most striking instance is afforded by the diamond. The amount of

heat required to change the temperature of a diamond by, say, 1 degree, diminishes rapidly as the diamond is cooled. Now heat is a form of energy, and the particular form which it takes, in the case of a solid, is that of a very rapid vibration of the atoms of the solid about their normal positions. We have to explain why an atom of a diamond at the temperature of liquid air should take up much less heat when brought into contact with some warmer body than, for example, an atom of lead. One might perhaps suppose that the difficulty could be explained, or at least shelved, by merely ascribing it to a difference in the chemical nature of the substances, but this will not do.

Clarke Maxwell showed, as the result of calculations of great difficulty, but undoubted correctness, that on the ordinary dynamics of Newton all atoms should require the same amount of energy to increase their temperature by equal amounts. Nor would this conclusion be markedly affected by the changes introduced by the theory of relativity. An explanation can be given if one is prepared to extend the quantum conception. So far it has been concerned with the frequency of the rather hypothetical waves of radiation.

Suppose a similar result holds for the frequency of the oscillation of an atom caused by heat. Suppose, in other words, that if such an atom is to vibrate at all it must vibrate with an energy corresponding to a quantum of its particular frequency, and that if it cannot get this amount of energy it must remain entirely quiescent. Now the diamond is very hard and its atoms rather light, and both causes make the vibration, if it exists, a very rapid one—frequency very large. With lead, the reverse. A large frequency means a large quantum of energy, and we would at first think that this went exactly the wrong way; that the diamond with its larger quantum would absorb more heat than the lead with its small one.

To understand why the reverse is the case, we must consider how the heat would behave on the old theory. When the diamond is put in contact with the body that is to warm it, there would naturally be an inflow of energy. Energy in the form of motion would be transferred from the rapidly moving atoms of the hot body to the more slowly moving atoms of the cold diamond. When a large group of atoms are left together, and so arrive at the

same temperature, their energies are not indeed all the same; but there should be a certain average or most probable energy, and big deviations from this energy are very unusual. The distribution of energy between the atoms is rather like the distribution of wealth in the community. If the average income is, say, £500, there will probably be individuals with incomes of £10,000, but they will be rare. Individuals with an income of £100,000 will be rarer still. Perhaps only one in a million will be so fortunate. This is what we may regard as the normal distribution. On the old theories it is the only one possible, and even on the quantum theory it will be approximately true at high temperatures when much energy is available for distribution.

But on the quantum view the diamond atoms at a low temperature are in the position that unless they are millionaires they can have nothing at all, and the chance of their being millionaires in a poor community is so slight that the average amount they possess is very small. One can illustrate the difference between the transfer of heat to lead and to diamond by comparing it to the selling of

Ford cars and Rolls-Royces. The amount paid for each Rolls-Royce may be twenty times that for a Ford. But if a community is limited to buying Rolls-Royces the number of people rich enough to acquire one is so small that the total amount paid will be less than if they were limited to buying Fords. The diamond atoms practise economy, so to speak, by refusing to buy anything but the most expensive. One can well understand that a consideration of this kind becomes more and more important the less the average wealth of the community. If one person in fifty could afford a Rolls-Royce, there might not be so much difference between the total amount that would be spent on them and the amount that would be spent on the Fords; but if they all became poorer, so that only one in ten thousand could afford a Rolls, the takings of Rolls-Royce would fall enormously, while there might still be enough people left who could afford a cheaper car to make the sale of that quite a profitable matter. Now the temperature corresponds to the average wealth in energy of the atoms, and we see why the restriction to a large quantum of energy operates more forcibly at a low tem-

perature. The experiments show that, in fact, the heat capacities of the diamond and other substances vary with temperature in just the way that is predicted on this view.

CHAPTER X

THE STRUCTURE OF THE ATOM (1): THE NUCLEUS

We have seen that there is reason to suppose that atoms are composed each of an equal number of electrons and protons, and the question naturally arises as to how much it is possible to discover about the arrangement of these constituents inside the atom. This is a question which has occupied the keenest attention of physicists for the last twenty years, and the problem is not yet completely solved. There are, indeed, indications that in certain respects the answer must for ever remain incomplete; but whether this be so or not, one point at least has been so firmly established that it may be regarded as certain. This is the theory, originally due to Rutherford, which regards the main mass of the atom as concentrated in a region very small compared even with the not very ex-

tensive dimensions which we have seen reason to assign to the atom as a whole. The theory took its origin from a series of experiments which at first sight might not have been expected to have been of very fundamental importance. Among the alpha-ray tracks in a Wilson chamber a few are seen with definite sharp bends, showing that their path has been deflected by an encounter with a molecule of the air. These deflections are tolerably rare except quite near the end of the track when the particles are going slowly. As a consequence of this effect, if a number of alpha-rays were originally all moving in the same direction they would tend to spread after they had gone some distance in the air. Some would have been scattered to the sides. A similar scattering will take place if the rays are sent through a thin layer of a solid instead of through the gas. Rutherford's original experiments were made on the scattering of alpha-rays by thin gold leaf. A narrow beam of the alpha-rays from a radio-active substance was selected by allowing it to pass through a small hole in a screen. After passing through the hole it struck the gold leaf, and the rays that passed through, after spreading for a few

inches, struck a fluorescent screen where their scintillations could be observed. By examining different portions of the screen with a microscope, and counting the number of scintillations per second, it was possible to determine the proportion of the rays which were deflected through various angles.

The great majority of the rays showed only very slight deviations from their original direction, but there were a few which showed quite big ones. Some, even, were so much deflected that they came out of the gold leaf on the same side as they came in. Though these big deflections are few in number, they are much the most interesting because of the information that they give about the inside of the atom. If one regards the atom as composed of electrons and protons, it can first be shown that these large deflections cannot be caused by collisions of the alpha particle with the electron. The reason is that the electrons are not heavy enough. A simple illustration will make this clear. Supposing one represents the protons and electrons in the atom by billiard balls and ping-pong balls respectively, and that one arranges them in some pattern on a billiard table. If another billiard

ball is shot at them the ping-pong balls will hardly deflect its path. Any big deflection which it experiences must be due to a collision with something at least comparable in mass to itself. To give such a large deflection that the alpha-ray comes out of the same side of the foil as that at which it entered, the alpha-ray must have collided with something more massive than itself. Thus there must be collections in the atom of more than four protons into particles which behave as a unit for collisions with alpha-rays. Rutherford tried the supposition that all the protons were collected into a single mass which he called the Nucleus. For a gold atom such a mass would weigh nearly fifty times as much as the alpha-ray and behave practically as though rigidly fixed. The scattering depends on the nature of the force between the alpha-ray and the nucleus. For example, suppose the forces were like those between billiard balls, i.e. no force until they actually hit and then a very large one during the moment of impact. Imagine a series of billiard balls shot at a fixed one representing the nucleus. They will come off it in all directions depending on the angle at which they happen to hit, but some

directions are more likely than others. For example, there will not be very many which are only slightly deflected, for this corresponds to a very fine shot, which, if the balls are not specially aimed, is unlikely. On the other hand, there will be a number with about the deflection corresponding to a half-ball shot, for this is a probable kind of impact. Now the alpha-rays do *not* show a result of this kind. On the contrary, small deflections are the most probable, and the chance of a deflection gets less and less the bigger the deflection. Suppose instead that the nucleus and the alpha particle behave as positively electrified points, they will repel each other according to the inverse square of their distance apart. If the alpha-ray were going originally straight at the nucleus, it would be brought to rest by the repulsion and driven back. In the much more likely case in which the alpha-ray is aimed a little to one side, it will be deflected by the repulsion. The closer it passes the nucleus the greater the force, and the greater the deflection.

It is a not very difficult piece of dynamics to calculate the way in which the scattered rays will be distributed among the angles.

The result agrees excellently with the experiment. Further, from the actual number scattered the strength of the repulsive force can be found. This depends on the product of the charges of the nucleus and alpha-ray. That in the alpha-ray is known to be two units, so the charge on the nucleus can be calculated. The experiments have been made for gold, platinum, silver and copper. In all cases the charge on the nucleus is equal within the error of experiment to the atomic number.

This most important result gives an immediate explanation of why the atomic number plays such a fundamental part in the classification of the elements. In particular it gives a rational explanation of Moseley's discovery that the wave-lengths of the X-rays characteristic of the elements, change in a regular manner along the series of increasing atomic number. For as the charge on the nucleus increases by a unit at a time the strength of the electric action near it will increase by regular stages, and if, as there is reason to believe, the characteristic X-rays depend upon effects in this region, one can understand that their wave-length might be expected

to change regularly with increasing atomic number.

The theory also offers an explanation of the existence of isotopes, i.e. elements of different atomic weight but with the same atomic number and chemical properties. The theory supposes that all the heavy particles (i.e. protons) are concentrated together in the nucleus. Now the number of protons is equal to the atomic weight in terms of hydrogen. It will be remembered that the atomic number is the number of the elements in a series, arranged with a few exceptions in order of increasing atomic weight. Except for hydrogen it is never more than half the atomic weight. Thus the number of protons is at least twice the atomic number. If, therefore, the atomic number is equal to the charge on the nucleus, the charge of some of the protons must be neutralized. This must mean that the nucleus includes a considerable number of electrons. We might indeed have expected something of the kind, because it is difficult to see how a collection of protons by themselves could hold together against their mutual electric repulsion. The introduction of about half their number of electrons helps to hold them to-

gether, because of the attraction between negative and positive charges. The electrons, in fact, may be regarded as acting as a kind of cement to hold the protons together. Now the theory suggests that the rôle of the nucleus in the structure of the atom is to act as a positively charged particle holding by its attraction the remaining electrons of the atom which do not form part of it. The effect of this attraction depends simply on the net charge on the nucleus, the difference that is, between the number of positive protons and negative electrons. If, then, we could introduce into a nucleus an additional pair of one electron and one proton there would be no change in the net charge. From the point of view of an electron in the outer parts of the atom there would be no difference. Now it is the outer electrons which determine the chemical forces, and indeed most of the physical properties, so that such a change in the nucleus would leave these practically unaltered. It would, however, increase the atomic weight by 1 unit and we should have 2 atoms of practically identical properties but different weight.

This is precisely what has been observed.

Isotopes of an element, then, are atoms whose nucleus has the same net charge, but contains different numbers of positives and negatives. When isotopes were first discovered it was suggested that each should be spoken of as a separate element, but apart from the inconvenience of having to speak of elements of indistinguishable properties, the quantity which really matters for nearly every purpose is the charge on the nucleus. It is much more convenient to treat as the same element all atoms which have the same nuclear charge irrespective of their weight. Such atoms will have the same chemical properties.

The isotopes of the same element never differ very much in weight. It is not obvious why this is so. Apparently if the difference in the number of protons and electrons is fixed, the numbers of each which can combine into a stable nucleus cannot vary very much. It is for this reason that the order of the elements arranged by atomic weight is not very different from the order arranged by nuclear charge, it being realized, of course, that the atomic weight, as measured chemically, is an average weight of the various isotopes of which the element is composed.

Apart from its function of forming a centre round which the remaining electrons are grouped, and of determining the mass, the nucleus also determines the radio-active properties, if any, of the atom. The connection between nuclear charge and chemical properties is, indeed, well illustrated by the properties of the radio-active elements. Since an alpha particle carries a double positive charge, the result of an alpha particle leaving the nucleus is to decrease the nuclear charge by two. There is a change in the chemical properties corresponding to a shift backwards of two places in the periodic table. Thus radium itself, which chemically belongs to the group known as alkaline earths, looses an alpha particle and becomes a gas called Radon, which is chemically inert. Now throughout the periodic table each inert gas is followed in the next place but one by an alkaline earth. Corresponding changes in chemical properties have been formed to occur in all cases of alpha-ray emission. With the beta-rays, on the other hand, we are dealing with a single negative charge, and the emission of this will increase the net charge of the nucleus by a unit. There is a shift of one place in the opposite direction,

which is also borne out by experiment. Now suppose, as sometimes happens, that there is an alpha-ray change followed by two successive beta-ray changes, then although the nucleus has been steadily loosing matter it will have recovered its original charge, and will have become an isotope of itself. Such cases have been observed. But though the chemical properties of these isotopes are identical, their radio-active properties are not, because on this view radio-activity is essentially a property of the nucleus, and the internal nuclear condition will be quite different in the two cases. This, again, is confirmed by experiment, and cases are even known where a radio-active atom is an isotope of an element which can also exist in a non-radio-active form. Thus there are radio-active leads chemically inseparable from ordinary lead, part of which is itself probably the final inactive product of a series of radio-active transformations. These results are very strong evidence for the view that radio-activity is a disruption of the atomic nucleus, and that the nuclear charge determines the chemical properties.

Nothing that we have said so far gives any

idea as to what size can be assigned to the nucleus, but a calculation of the paths of the scattered alpha particles shows, in the case of gold, that the nucleus continues to act as an ideal point charge even when the alpha-ray approaches to a distance of $\frac{1}{10000}$ of the radius of the atom. The repulsion between the large charge (79 units for the gold nucleus) and the alpha-ray is so great that even these vigorous atomic projectiles cannot approach much nearer than this. With atoms of the lighter elements the repulsive force is less, and the alpha particles can, in favourable circumstances, get still nearer. Scattering experiments with these light elements show that the inverse square law of repulsion ceases to be true at a distance somewhat less than the above, and the results suggest that the size of the nucleus is somewhere about $\frac{1}{100000}$ part of the size of the atom.

The process by which such an estimate is arrived at is a very much less direct one than that used in the measurement of atomic dimension. In the case of atoms the size was deduced from experiments on crystals. It was found that, in fact, the atoms do pack together much as though they were spheres

of a definite size filling the space of the crystal, and since we know the number in a given volume the deduction of the dimensions is a fairly straightforward matter. It is true that the values deduced for the same atom from different crystals are not always quite the same, and to that extent there is a certain vagueness. The deduction of nuclear size is far less direct, there is no question of packing the nuclei together in contact. All one can say is, that if the interpretation of the experiments is right, then there is a change in the nature of the forces when the nuclei approach within this distance.

The collision of alpha particles with the lighter nuclei has been studied by the Wilson track method. In the case, for example, of air, the nucleus is not more than four times the weight of the alpha-ray, so that in any collision in which it undergoes a violent deflection the alpha-ray will, by its reaction, give a considerable velocity to the nucleus. This may be enough to make the nucleus produce ions by collision, in which case the track will show a fork, one branch being due to the original alpha-ray and the other to the nucleus which it has struck. In the case of hydrogen,

where the nucleus is a single proton and so actually lighter than the alpha-ray, the speed of the nucleus after the collision may be greater than that of the original ray, and its track correspondingly longer.

Rutherford has studied the fast protons produced in this way. He used a fluorescent screen placed out of range of the original X-rays, so that only the protons could reach it, and observed the scintillations. He made the very remarkable discovery that a few long-range particles were found even when no hydrogen was present. Now no other atom is lighter than an alpha-ray, and it seemed impossible that any other could cause the effect. He was driven to the conclusion that, very occasionally, the collision of an alpha-ray with certain atoms—for example, nitrogen—could release a proton from the nucleus, with nearly as much speed as if it had been part of a hydrogen molecule.

This marks a further stage in the disintegration of the atom. Radio-activity is a spontaneous disintegration of the nucleus; here for the first time is one artificially induced. The effect has been found in a number of the lighter elements. In the case

of aluminium the velocity of the proton is exceptionally high, so large, in fact, that the collision must cause a gain in energy.

Physicists have for some time discussed the possibility of deriving useful energy from the interior of atoms, and striking figures have been given of the power which might conceivably be derived from small quantities of matter. In view of the above experiment it is of interest to consider the evidence on which these ideas are based. First there are the known facts of radio-activity. The fast rays ejected carry energy which, when they are absorbed, appears as heat. In practice the amount so obtained is small, because those radio-active substances which break down rapidly are available only in very small quantities, and the others take too long about it to be of practical value. Thus a pound of uranium would give enough energy to take a liner across the Atlantic, but it takes a thousand million years to give it! There is no known means of hurrying up radio-active change. Even bombardment by the rays from other disintegrating atoms has no effect. Radio-activity is therefore of no practical use as a source of energy.

There is, however, good reason to suppose, firstly that the existence of atomic energy is a much more general property of matter than is radio-activity, and secondly that circumstances exist in which very large stores of this energy are, in fact, released. The reason for the former supposition is based upon a result of the theory of relativity. According to this, mass and energy are practically synonymous, the mass of a body representing its internal energy, and any change in the energy being accompanied by a corresponding change in mass. The relation between the two, however, is such that a little mass corresponds to a great deal of energy, so that most of the ordinary changes of energy would correspond to a change of mass too small to be measured. On this view when, for example, we burn a piece of coal the weight of the products of combustion (gases and ash) is not exactly equal to the weight of the coal plus the weight of the oxygen used to burn it. It is really slightly less, because the balance has gone in energy, but the difference in this case is extremely minute—only about one part in 2,000,000,000. But though the effect is generally so small, we have already had one in-

stance where it becomes measurable. The mass of a very fast beta-ray may be several times as great as that of a slow electron. The mass has increased because of the energy of motion. If this connection of mass and energy is accepted as perfectly general it affords the explanation of the anomalous atomic weight of hydrogen. The reader will remember that after starting with the weight of the hydrogen atom as the unit in terms of which all other atomic weights were to be measured, we were led in practice to abandon it. If we had kept it the atomic weights would have come out fractional, while by taking instead $\frac{1}{16}$ of the weight of the oxygen atom as unit, the weights all come out very nearly integers with the exception of hydrogen itself, which is now, not 1, but 1.008. If we knew nothing about atomic structure we might simply suppose that we had, in fact, made a rather unfortunate choice in fixing on hydrogen as a standard. But we have seen that it is extremely probable that all atoms are, in fact, made up of equal numbers of electrons and protons and that hydrogen has one of each. The only conclusion one can come to is that in some way the proton, when it forms part

of a complicated nucleus, has very slightly less mass than when it exists by itself as the nucleus of a hydrogen atom. Of course one might suppose that the hydrogen proton was a different thing from the protons of the other elements, but it seems very surprising that it should be nearly the same and not quite. It seems queer that nature should trouble to make a difference at all if it is only to be a paltry eight parts in a thousand.

The relativity view is a much more attractive one—the difference in mass simply means that when the protons combine with their cementing electrons to form a complicated nucleus a certain amount of energy is set free, about the same in all cases. There will thus be a certain loss of mass. The amount of energy corresponding to this loss is very large, and in fact the energy which would be released by the hydrogen is more than thirty times that given by an equal weight of uranium going through its complete series of radio-active changes.

Now Aston has found recently that the weights of the atoms, though very nearly integers in terms of the unit which we have chosen, do in fact show just measurable diver-

gencies from the whole numbers. This must mean that the loss of energy per proton is not quite the same for all nuclei. In other words, the nuclei of some atoms have rather more energy than others. Though the differences in weights are so small as to require the greatest skill to measure them, the corresponding differences in energy are very big, and it seems that large stores of energy should be obtainable if it were possible, for example, to transform the nucleus of an element whose atomic weight is a little over an integer, into two nuclei whose weights were each a little under the integral value. Alternatively we might hope to get energy by building up a nucleus whose weight was a little below its proper integer by combining two others whose weights were a little in excess.

Rutherford's disintegration experiments are the first direct proof of these possibilities. The energy of the ejected proton may, of course, be derived from that of the original alpha-ray, and a break-up of the atom might even occur which required an absorption of energy; but in the case of aluminium, where the proton comes off with more energy than the alpha particle had, we have the first clear

case of the artificial production of atomic energy. It is true that the whole scale is excessively minute. The atoms so produced were actually detected by counting them. In fact, if the whole of the radiation from a gramme of radium, worth at present prices £12,000, were absorbed in aluminium for a year, the amount of hydrogen produced could barely be detected by the most sensitive experiment, and the energy set free would be only an infinitesimal fraction of the energy of the radium. The reason is that the chance of hitting a nucleus in such a way as to produce disintegration is excessively small. This is partly owing to the small size of the nucleus, and partly because from the nature of the case the alpha-rays are fixed entirely at random. It is rather like trying to fire a cocked and loaded gun by shooting rifle bullets at the trigger from a mile range on a dark night.

The study of the results of these collisions in a Wilson chamber has brought out the interesting fact that the alpha particle stays inside the nucleus after the collision. This is shown by the fact that the track corresponding to the disintegration of an atom shows a fork with prongs of unequal length. The long

prong corresponds to the fast proton produced by the collision; the short prong to the rebound of the rest of the nucleus. There is no third track such as would be caused if the alpha particle continued on its course. It follows that what seems like a process of breaking down an atom is really one of building up, because the nucleus gains 4 units of weight and loses 1.

Though atomic energy is apparently so insignificant from the practical point of view, it is probable that in reality we owe to it our whole existence, for all life depends on the sun, and it is becoming increasingly probable that the sun's heat is, in fact, supplied from this source. There are varying converging lines of argument which have led to this belief and which have recently been put forward by Sir James Jeans in his book *Astronomy and Cosmogony*. The first reason is the difficulty of finding any other source adequate to supply the immense quantities of energy which the sun is radiating. It is fairly certain that the earth has lasted in a condition not very different from the present for at least one thousand million years. In all probability the sun has lasted very much longer, but even taking

the figure given, most of the ordinary sources of energy are completely ruled out. For example, the energy which would be released by the most active chemical changes known, such as combustion, would not supply one part in a hundred thousand of that required. If the sun were shrinking, the falling in of its mass would generate energy, and it was supposed at one time that this might be adequate to account for the heat. But this will only account for a few per cent. of the life now assumed by the earth. Radio-activity is at first sight more promising. Jeans has calculated that 1 part in 800,000 of radium would account for the present heat production, and this sounds quite promising, but unfortunately radium disappears at such a rate that even if the sun were originally solid radium there would be less than this left after only a million years. A sun of solid uranium would give nearly enough heat and would last nearly long enough, but there is no evidence of any appreciable amount of uranium in the sun, the upper layers of which, at least, are known from their spectrum to be formed of quite ordinary material. Further, there are plenty of stars quite like the sun whose rate of heat

production is markedly greater, and so the radio-active hypothesis must be abandoned.

There are two forms in which the theory of atomic energy has been applied to astronomy. The less drastic is to suppose that the energy is derived chiefly from a combination of free protons, i.e. hydrogen, to form complicated nuclei with an evolution of heat corresponding to the loss of mass. This would give plenty of heat to keep the sun going for the thousand million years which the earth has lasted. But there are some reasons to suppose that in fact the stars have lasted for very much longer periods than this, periods of the order of a million million years. Even the energy of nuclear combination would be inadequate to keep stars shining for such a time as this. It is a very significant fact that the heaviest stars are the stars which are most energetic in radiating, even in proportion to their weight. Further, there is reason to suppose that they are also the youngest. This has led Jeans to the supposition that the stars are, in fact, consuming their own mass, and that the younger stars are more energetic because they contain more of some easily consumable constituent.

Now the diminution of mass as the result of the combination with hydrogen is only 8 parts in a thousand, while if it is right to suppose that the lighter stars are so, chiefly because their mass has been consumed, it would mean that perhaps 90 per cent. of the original mass was capable of disappearing in this way. This involves some process still more drastic than any we have considered. Jeans boldly suggests an actual destruction of units of matter, and considers it possible that under certain conditions which can only be guessed at, an electron and proton may come together, neutralize one another's charges and cease to exist. Their mass would then, so to speak, be disembodied, and would have to appear as energy of radiation. On this view the material universe would be melting away into radiation which would travel out into the depths of space. Whether this radiation in any conceivable circumstances could reform electrons and protons is a question at present so purely speculative that no opinion can be reckoned more than a guess. All one can say is, that there is not the slightest evidence to indicate that any such converse process is, in fact, occurring; but if it does

not, then the universe is steadily running down and consuming its substance to provide energy for its activity. It will, of course, be understood that the possible destruction of mass is something quite different from a mere combustion such as occurs with burning fuel. This involves practically no change of mass but only a change of chemical form, the solid coal combining with the air to form gaseous products which disappear up the chimney.

In the last few years the hypothesis of atomic changes in the heavens has been strengthened by a further piece of evidence. A form of radiation has been found naturally present in the atmosphere and much more penetrating than the hardest gamma-rays from active radiation. This radiation has been detected by a slight ionization which it produces and which is found to increase at great altitudes, as proved by experiments in balloons. While it is possible that this radiation is the after effect of distant thunder-storms, it has been suggested that it comes from sources altogether outside the earth. Millikan has measured the penetrating power by observing the diminution in the effect when the instruments for detecting the ionization

are submerged in a lake. From the penetrating power it is possible to give a rough estimate of the wave-length, and hence by Einstein's law, of the energy of a quantum. The rays are not homogeneous, and vary in penetrating power, but for the most penetrating, the amount of energy is at least as large as would be released by the combination of 4 hydrogen atoms to form 1 of helium. Perhaps we have here a message from the parts of space where atomic transformations are in progress. It has been suggested that the most penetrating of the rays have too much energy even for this, and are the consequence of the mutual annihilation of protons and electrons. The effect does not seem to come especially from the sun; it is disputed whether the Milky Way has an important influence. In any case it is intrinsically probable that if the process is a general one the most important contributors to the radiation would be the Great Nebulæ. In a case like this the closer distance of the sun and nearer stars would probably not compensate for their vastly smaller size.

If this view of the source of the sun's heat is correct, it makes the chances of releasing

atomic energy on the earth seem rather brighter. We do not know what causes the release of energy to take place in the sun and not in the earth, but if the matter which is changing in the sun is like that which we have on earth it would seem by no means a hopeless task to make it change artificially. The material on the surface of the sun is formed of the same elements which we have on earth. This is shown by the identity of the spectral lines. Jeans thinks that the matter which is disappearing is in the form of elements heavier than any known on the earth. If these constitute a large fraction of the sun's mass it is surprising that no spectroscopic evidence of them has been found. It is just possible that the matter which undergoes these changes may be unstable isotopes of known elements, whose spectra would therefore be indistinguishable, but this is purely an *ad hoc* hypothesis. The other possibility is that the matter which is disappearing is quite ordinary matter, and that it is disappearing because of the special conditions in the sun. The most obvious of these conditions is very high temperature. It is probable that the temperature of the centre of the sun is of the

order of thirty million degrees. Jeans, however, is strongly of the opinion that temperature alone is not likely to be the cause. Roughly speaking, the argument is this. If the release of energy is a temperature effect, then the hotter the star gets the more energy will be released and this will make the star hotter still. Thus the effect would be unstable, and once it began, the star would explode.

One may sum up on the chances of atomic energy as a practical proposition as follows. It is practically certain such energy exists; it is very likely that it is being released on an enormous scale in the stars. It is somewhat doubtful whether suitable material exists on the earth. If it does, it is perhaps not unduly optimistic to suppose that man will some day be able to imitate this most violent of natural processes. If he does, the stores of energy available are so vast that for all practical purposes they are infinite. The complete destruction of a few pounds of earth would provide energy for England for years. How much difference this would make in practice would depend largely on how complicated was the machinery necessary to set free the energy.

It might be only practical on a large scale, in which case costs of transmission and interest on the capital value of the machinery would become the determining factor. The actual cost of the power to the small consumer might not be very different from what it is at present to people living within a few miles of Niagara, where power is provided by nature for the cost of collection. On the other hand, it would completely revolutionize manufacturing processes on a large scale, for the energy involved in a process would cease to be an important factor in its cost. It is an interesting question whether it would put an end to coal mining and oil production. At first sight one would think that it certainly would, but it is quite possible that in the future coal will be mined, as much for the sake of its by-products as for the energy which it gives. In addition, if at first at any rate the atomic energy could only be produced on a very large scale, it might not be suitable for use in a motor-car or even on board a ship, and oil and coal might continue in use for these purposes.

CHAPTER XI

THE STRUCTURE OF THE ATOM (2): ENERGY LEVELS

It has been explained in the last chapter why it is believed that all the protons in the atom, and some of the electrons, are combined to form a very small particle called the nucleus. The next three chapters in this book will be largely devoted to an attempt to explain what is believed to be the condition of the remaining electrons. Since the charge on the nucleus is equal to the atomic number this must also be the number of the electrons outside the nucleus, for the atom as a whole is electrically neutral. The task of explaining the arrangement of these electrons would have seemed considerably easier five years ago than it does now. It was then believed that these electrons moved in orbits round the nucleus in a way closely resembling the motion of the planets round the sun. The Solar system

seemed to form a kind of natural model on a gigantic scale of the interior of an atom, the sun representing the nucleus and the planets the electrons. In the last few years, however, this view has been shown to be inadequate; and although we are now in possession of a theory which shows every prospect of being ultimately satisfactory, it unfortunately does not lend itself nearly so readily to a concise and non-mathematical statement as did the older one. The invention and development of the planetary theory was largely due to the great Danish physicist Niels Bohr. Though much of this work has had to be modified in the light of more recent knowledge, much remains, including the substance of the rest of this chapter, and even the errors were probably a necessary stage which had to be passed. Even if the present theory could have been invented without the background of the older one, it would probably have been rejected as too revolutionary. The older theory prepared men's minds for a still greater break with the traditional views, and by emphasizing the impossibility of an explanation on these lines made the way easy for new ideas.

In view of these changes of belief it seems

highly desirable in dealing with this problem to try as far as possible to state first what is definitely known from direct experiment and to keep to as late a stage as possible the introduction of theoretical explanations. The first outstanding fact in the theory of these extra nuclear electrons is the existence of what are called Energy Levels. The idea is that each electron in the atom requires an amount of energy to remove it completely from the atom, which is characteristic of the particular atom, and the particular electron, though more than one electron may be at the same energy level. The electrons in the atom may be likened to the water in a canal kept by locks at a variety of different levels. Between each pair of locks the water is at a definite level. Take some great height, say the reservoir from which the canal is filled, to correspond to complete removal. Then the energy required to lift say a pound of water from some level of the canal to the reservoir is analogous to the energy required to remove an electron from the corresponding "energy level." This idea sounds so simple that it is perhaps just worth mentioning that it is definitely contrary to what one would expect if the electrons be-

haved like a swarm of particles subject to ordinary mechanical laws. The particles of such a swarm would as a general rule be perpetually interchanging energy one with another, and there would be no definite amount of energy permanently associated with any. Some of the evidence for this view comes from experiments which we have already described; thus the existence of what we called the ionization potential implies that there is one electron at least in each atom which can be removed if a certain definite amount of energy is supplied to it by collision with a rapidly moving free electron. Actually the ionization potential found by experiments of this type is only one among many. Any electron of the atom can be removed by a collision with a free electron of sufficient energy, and the ionization potential we have so far considered merely represents the energy required to remove the particular electron which happens to be least firmly held. One might indeed speak of a number of ionization potentials corresponding one to each of the electrons in the atom.

Another type of experiment which, although not historically the earliest, is perhaps the

most convincing, is as follows. According to Einstein's theory of the photo-electric effect (see page 124) a quantum of radiation has an energy h times its frequency and can give the whole of it to a single electron. In the ordinary photo-electric effect the experiments are made with light of relatively moderate frequency in or near the visible. But suppose instead we use X-rays for which the frequency is enormously larger, then the energy of the quantum will be correspondingly greater, and it will be able to cause the emission not merely of the most loosely bound electrons but of the others as well. Suppose, then, that a beam of X-rays of sufficient frequency falls on a small piece of an element; it will cause the emission of electrons from all the possible energy levels, each quantum giving one electron. Now if the X-rays are all of the same frequency their quanta will all have the same energy, and each of the emitted electrons will have this energy, less the energy required to remove the electron from the particular energy level in which it happened to be. Thus the electrons from any large group of atoms, such as is formed by even a small portion of a substance, will consist of groups of electrons

of a number of various energies, one group for each energy level of the atom. It is possible experimentally to separate electrons of different energies by bending them in the magnetic field, and when this is done it is found that they fall as predicted into a number of definite groups. From the energy of any one group and that of the quantum of the X-rays used, the value of the corresponding energy level will be found by subtraction.

Another way in which the energy levels have been investigated is as follows. A quantum of radiation can only remove an electron if its energy is greater than that corresponding to the energy level of the electron. Now suppose a beam of X-rays is passing through a plate of some material, and that the frequency of the X-rays used is in some way gradually increased. When the frequency reaches a value such that the quantum becomes equal to the energy level of a particular group of electrons, these electrons will for the first time be liable to be ejected. The ejection of electrons of course robs the beam of X-rays of some of its energy, so that the absorption of a beam whose frequency is just a little greater than the necessary amount

will be suddenly more than the absorption of a beam whose frequency is just a little less. Experiments show that these discontinuities in absorption, or Absorption Edges as they are called, are extremely well marked, and the frequencies at which they occur when multiplied by h give the values of the energy levels.

As might be expected, it is found that the number of energy levels increases as the atom gets heavier, but the number is always less than the number of free electrons for which homes have to be found. Thus several electrons must inhabit each level. All atoms show some levels at energies of not more than about 20 volts. The limit at the other end increases with the atomic number from a value of the same order to about 120,000 volts, in the case of uranium. The general arrangement is one of groups of a few levels not differing much from each other, but separated widely from the next group. It is usual to call the levels which require much energy to remove their electrons "low" or "deep," for there is reason to suppose that the electrons in them are on the whole closer to the nucleus than those in the "high levels," but these terms must not be regarded as necessarily implying that

the levels are entirely a matter of position.

When an atom has been ionized by the removal of an electron from one of the levels it has an excess of energy over the normal and it rids itself of this excess by radiation. The empty level is filled by an electron coming down from one of the higher levels, and the difference of energy leaves the atom as a quantum of radiation which also obeys Einstein's law, i.e. its frequency is the available energy (in this case the difference between the two energy levels) divided by h. When the original electron came from one of the lower levels, this radiation will generally be in the X-ray region of the spectrum. In fact, the X-ray spectra studied by Moseley are accounted for in this way, so that Moseley's law of the regular change in the frequency of the X-rays produced by atoms of different atomic number really means a regular change, with atomic number, of the energies of the different levels.

Besides the levels we have been considering so far, each of which is normally filled by one or more electrons, there are other potential levels outside the normal atom into which an electron may be temporarily displaced either

by the impact of an external free electron or by the action of radiation. From these levels the electron rapidly returns to its normal position emitting a quantum of radiation whose frequency is determined by the same rule as before. We have already come across an instance of one of these levels in the resonance of radiation described on page 116. These outer levels only differ by a few volts from the nearest normal positions, and consequently the radiation is of comparatively small frequency and generally comes in the region of the visible spectrum. It is found that this view fits in extremely well with the observed frequencies of spectral lines. These can all be regarded as derived from the difference of two energy levels divided by h. In this way the apparent complexity of spectra is greatly reduced, the spectrum of any one element being derived from a comparatively small number of energy levels taken in pairs to give their differences.

The first stage in the analysis of the spectrum of an element consists in finding suitable energy levels to give the observed lines by a process of subtraction. It is further found that these energy levels, at least in the case

of simple spectra, show a curious relation to whole numbers. To explain the nature of this relation we must venture on a few simple algebraical expressions. The atom of hydrogen as the simplest atom has quite naturally the simplest spectrum. It consists of groups of lines arranged in a manner which obviously indicates a regularity of formation. Three such groups or *series* as they are called are well marked. Their frequencies are represented by the expressions,

$$N\left(1-\frac{1}{n^2}\right),\ N\left(\frac{1}{2^2}-\frac{1}{n^2}\right),\ N\left(\frac{1}{3^2}-\frac{1}{n^2}\right)$$

where N is a certain number and n is any one of the series of whole numbers, running 2, 3, 4, etc., in the first case, 3, 4, 5, etc., in the second, and 4, 5, 6, etc., in the third. Note first that these formulæ fit the rule that we have given; the frequency is the difference of two quantities. Further, the corresponding energy levels (or terms as they are usually called in dealing with spectra) are of the form $\frac{Nh}{n^2}$ and thus go inversely as the squares of a series of integers. This peculiar result—and something of the same nature in a slightly more complicated

form holds for other spectra—suggests a new kind of atomicity inside the atom itself. Not merely is the atom composed of integral numbers of primitive constituents, electrons and protons, but their grouping, at least for the electrons outside the nucleus, is governed by whole numbers.

The various theories which in the last few years have attempted to describe atomic structure have chiefly been concerned in finding a plausible explanation for this curious rule. In more complicated spectra an important extension appears, and a level is characterized not by a single whole number but by a group of several whole numbers, in the most general case by 4. If for the purpose of making a picture we regard the existence of an electron in a particular energy level as denoting its position in a certain place, this rule means that 4 quantities are required to determine the place. Imagine a city drawn up on the American plan with all the streets numbered and each street containing a number of blocks of flats, then one might think of one number as determining the street, a second number the house in the street, a third number the flat in the house, and a fourth number

indicating the particular room in the flat which the electron is inhabiting. It will readily be seen that electrons with any of these numbers in common will be likely to have certain peculiarities in common. Thus one set may all be ground-floor apartments, another set all in one street and so on. These numbers which give, so to speak, the address of the electron, or rather of the level, are called quantum numbers, though we have yet to explain how the quantum comes into the matter. It will be remembered that the number of levels inside the atom is less than the number of electrons. It appears that this is partly accidental. If the atoms are placed near a powerful magnet, some of the levels which before were equivalent became different, as shown by a splitting up of the spectral lines. It seems almost certain that the number of positions when fully distinguished by their quantum numbers is just equal to the number of electrons; but some of these positions, at least under normal circumstances, are equivalent as regards energy. Thus each electron has a definite address, and only one electron is allowed in a room at a time. This principle holds both for the levels that are normally

occupied and for those in which the electron can only stay temporarily. Overcrowding is thus forbidden by law in our imaginary atomic city—a principle known as the Pauli Exclusion Principle. A further peculiarity is that one of the four quantum numbers is hardly a number at all, for it is limited to only two possibilities, as though each flat had only two rooms and these were related together something after the fashion of a right- and left-hand glove. It is, however, more convenient to distinguish them by assigning to one the number $+ \frac{1}{2}$ and to the other $- \frac{1}{2}$. The reason for this choice is that it allows of a simplification of the rules by which the energies are related to the quantum numbers.

CHAPTER XII

THE WAVE THEORY OF MATTER

Until the last three years the quantum numbers spoken of in the last chapter were regarded as determined by the shapes and sizes of certain orbits in which the electrons were supposed to move like planets round the sun. In spite of many remarkable successes, especially in the explanation of spectra, this theory gradually became untenable, and has been replaced by a theory which, though starting from a totally different standpoint, yet manages to repeat the success of the older theory in the explanation of spectra and is free from the outstanding objections. The theory owes its origin to Prince Louis de Broglie, and has been largely developed by Schrödinger and others. In the present chapter we will give some account of the theory, which is of an extremely fundamental and comprehensive nature, and leave for a later

chapter its application to atomic structure.

There has been a tendency for some time to believe that the solution of the photo-electric paradox (see page 127) would be found in some combination of the ideas of waves and particles by which the particle could carry the energy, and the wave in some way determine the motion of the particle. Einstein's law is readily explained if the energy in radiation is in fact collected into individual particles travelling with the velocity of light, and each having an amount of energy h times the frequency. There is nothing unreasonable in supposing that such a particle could deliver its whole energy to an electron of a body through which it was passing, and this is all we need. In a beam of light the energy of each particle will be determined by the wave-length, since this is inversely proportional to the frequency, while the number of particles in the beam would depend on its intensity. Thus the speed with which the electrons are ejected would be independent of the intensity of the beam, if we exclude the extremely unlikely possibility of one electron being hit simultaneously by two particles.

So far this is purely a corpuscular theory

and as such open to the objections which led to the abandonment of the old corpuscular theory at the beginning of the nineteenth century. These facts were Diffraction, the process by which light bends slightly into shadows, and Interference in which the addition of two beams of light produces blackness in certain places, compensated by increased brilliance in others. If, however, we abandon the idea that the particles naturally go in straight lines, and consider their motion as determined by a system of accompanying waves, it is possible to devise a scheme by which the particles would appear in great number where the waves were strong and be few where the waves were weak. If number of particles determines intensity, this would give a distribution of light and darkness identical with that obtained if light itself is regarded as waves. Such a theory is remarkably like the theory devised by Newton as a modification of his original corpuscular (i.e. particle) theory of light, when it became necessary to account for the effects of interference, some of the most striking of which were discovered by himself. It is a very remarkable episode in the history of science that this

theory discarded in the early nineteenth century as unnecessarily cumbrous should have reappeared as a consequence of discoveries, such as the photo-electric effect, which were undreamt of at the time when it was first invented. Such vitality is a remarkable tribute to Newton's amazing physical insight.

De Broglie's achievement is to give firm and logical foundation to this theory by showing it as part of a still more fundamental general principle. According to the theory of relativity, the laws of nature must be of such a kind that they are the same for all observers, no one observer being privileged above the others. Now the law we have used so far connecting energy and frequency is not by itself of this character, but it becomes so if we associate with it another law giving a connection between momentum and the wave-length of a certain wave. By momentum is meant the quantity which on the Newtonian mechanics is the product of mass and velocity. The new relation comes to asserting that any particle is associated with a wave whose length is the quotient of h by the momentum, or in symbols, $\frac{h}{mv}$.

Further, in the case where this wave-length is small the path of the particle is identical with the rays associated with the wave. It has long been known that the idea of a ray of light travelling in a straight line is only an approximation to the way in which waves are propagated, very nearly true in practice because in fact the wave-length of light is very small. Newton's first law of motion asserts that a particle in the absence of force will move at constant speed in a straight line. On the new view this is merely an approximation to a more exact law, bearing the same relation to it that the propagation of light rays in straight lines bears to the more exact laws which govern their slight bending. We have, in fact, turned the flank of the difficulty of the apparently peculiar behaviour of the light quanta by saying that it is really the natural behaviour to be expected from any sort of particle. But such a method of evasion obviously leads to the difficulty that it must explain why in fact other particles appear, at least, to move as Newton said they did. As far as the behaviour of bodies of ordinary size, and still more of large bodies like the planets, is concerned, the difficulty is met by the very

small value we have had to assign to the quantity h. The wave-length, in fact, is so small that the approximation of replacing waves by rays is for all practical purposes a perfect one. But for the smallest particles this is no longer the case, for an electron of energy corresponding to $1\frac{1}{2}$ volts (about the amount of energy possessed by the electrons near the filament of a valve) the wave-length is 10^{-7} or one ten-millionth of a centimetre, which though small is about 5 times the size of an atom. For cathode-rays of energy 15,000 volts, the wave-length is about one-hundredth of this, or about that of a hard X-ray. Now it will be remembered that the wave-lengths of X-ray were measured by using crystals to scatter them, the regular arrangement of the atoms in the crystal showing itself in the formation of relatively intense scattered beams in certain specially favoured directions. A similar process should be possible with the electron waves. Such experiments have in fact been made by Davisson and Germer in the United States and by the author and others in this country.

In the author's experiments cathode-rays are transmitted through a thin film of metal.

An ordinary metal is a collection of crystals of microscopic size held together by a non-crystalline cement. Each little crystal should have its own preferred directions in which the waves would tend to go. The effect on X-rays of passing through such a mass of tiny crystals has been thoroughly investigated, and has indeed found practical applications in metallurgy. If a narrow beam of X-rays passes through a metal and then is received on a photographic plate at right angles to the beam, the pattern formed is one of concentric circles having their centre where the rays would strike the plate in the absence of the metal. The sizes of the circles can be calculated from the wave-length of the X-rays and the structure of the crystal. When electrons are used instead of X-rays a difficulty arises from their very slight penetrating power. Instead of using a piece of metal of ordinary size, it is necessary to use extremely thin films less than a millionth of an inch in thickness. Such films are highly transparent. They offer no more obstruction to the light than a piece of slightly tinted glass; if held close to the eye one can see through them the individual bricks of a building across the road.

When films like these are used and the electrons received on the photographic plate arranged in the same way as for the X-rays, patterns are formed which are exactly similar in character to those formed by the X-rays in the same metal. But as the wave-length of the electrons is less, the whole pattern is rather smaller than for X-rays.

Complete agreement has been established with de Broglie's theory. The relative sizes of the rings are just what is to be expected from the known crystal structure of the metals. The variation in the size of the rings with the speed of the electrons is that predicted by de Broglie's formulæ for the wave-length, and the actual size of the rings is correct, in the mean, to 1 or 2 per cent. It seems certain that the electrons are associated with waves in the manner depicted by de Broglie. It has not been possible as yet to make an experimental test for any other kind of particles owing to the excessively small wave-length to be expected, but it seems highly probable that the theory is right in regarding the relation between waves and the motion of a particle as perfectly general.

But this theory raises many difficult prob-

lems. The results of the experiments make it necessary to suppose that the waves extend over a considerable region. The region indeed must obviously cover a considerable number of atoms, otherwise the effect of the regular spacing on which the whole thing depends could not come into play. But if one regards the waves as in any sense forming part of the electron, this means that an electron is larger than an atom, and how then is it possible for many electrons to form part of a single atom? It seems as though the whole conception of size as applied to an electron is a mistaken one. In the ordinary way one considers the space occupied by a body as the region within which it exerts a considerable force on anything trying to intrude. For an ordinary hard solid this boundary is a remarkably definite one and measurable with great accuracy, but even here there must theoretically be a slight vagueness, a force repelling an exploring body can hardly come into being with complete suddenness at a mathematical point. We saw in the case of atoms that probably an appreciable degree of vagueness must be allowed in their sizes, though in this case the size is sufficiently definite to be given

a rough measure. It would seem as though for an electron the size was nothing but the region in which it exerted force, that this region has no very definite boundaries and may be larger or smaller according to circumstances. Since an electron can transfer its whole energy by collision the energy must be highly concentrated, but it does not seem possible, at any rate at present, to assign to it any definite dimensions, and it is probably best regarded provisionally as a mathematical point. This gives us a picture of the electron somewhat resembling the tiny gossamer spiders which drift through the air, each at the centre of a number of diverging filaments. The wind catches the filaments and the spider is carried where the filaments take it. In much the same way the point which represents the energy of the electron is guided by the waves which surround it, and extend possibly to an indefinite distance in all directions. If the waves pass over an obstacle like an atom, their direction is modified and the modification is transmitted back to the electron and affects its path. Thus the waves act as a kind of intelligence system to the electron and enable it to guide its path in accordance with

the distribution of matter which it finds around it. Thus the electron may be influenced by atoms though it may never pass very near them, and the effect of a widespread regular structure is explained.

The question of the physical nature of these waves is a very difficult one. Ordinary material waves such as water waves, or the air waves which form sound, certainly require a medium to carry them, and in the case of light waves where there is no material medium in the ordinary sense of the word, the physicists of the past have found it necessary to invent a quasi material substance or Ether to which is entrusted the duty of carrying the waves. The modern tendency accentuated by the theory of relativity has been to make the ether less and less material, and to regard it as hardly more than another name for space. But even if a material ether is accepted it cannot without modification account also for the electron waves. All forms of light, whatever their wave-length, travel in a vacuum with the same speed. This speed is thus a constant of nature, and the development of relativity has emphasized still more strongly than before its constancy and fundamental character. Now

the waves that accompany an electron definitely do *not* travel with the speed of light. According to de Broglie's theory they travel much faster and the slower the electron the faster the waves. This theoretical result seems at first in contradiction to relativity, one of the fundamental ideas of which is that no signal can travel faster than light. But it is just here that the explanation comes. The electron waves as such cannot transmit a signal, for they do not carry energy. This is all associated with the electron, and observable effects can only be produced by the presence of the electron, and thus can only travel with its speed, which is of course always less than that of light. The waves, in fact, must be regarded as perpetually running through the electron from behind so that the electron is always receiving a fresh supply.

But there is a kind of peculiarity in the waves which is associated with the electron and moves with it. This peculiarity is called the "group." The condition can be paralleled to some extent in water waves, thus the bow waves of a ship are a disturbance of unchanging shape. If any such wave were formed in the open sea and left to itself it would break up

into a long train of waves, much as the splash of a stone in a pond starts as an irregular disturbance and reaches a distant shore as a regular series of waves. The velocity with which a disturbance like a bow wave spreads away from the ship is quite different from that of the simple wave which most nearly resembles it. Another instance is given by a rough sea. This hardly ever shows a regular train of waves like the conventional picture. Generally there are regions of intense disturbance alternating with patches of comparative calm. But the speed with which a region of disturbance moves forward is quite different from the speed of any of the individual waves which have gone to form it. The velocity of the disturbance is the "group" velocity as opposed to the velocity of the individual waves. In water waves, as in electron waves, the group velocity is the speed at which energy travels. For the electron waves the group velocity is equal to that of the electron, which thus moves with a constant group, though the waves of which the group is composed are perpetually moving through it. For most purposes the group velocity is what matters; indeed, the wave velocity seems of

the nature of a mathematical abstraction in that it is probably impossible to measure it directly.

It is possible to construct a theory which accounts for most of the facts on the view that the presence of the electron modifies the ether, and so modifies the speed of waves through it. But it seems equally likely that one should take a less material view of the nature of the waves. Fundamentally a wave is some effect which is propagated according to certain definite laws; and though this effect is generally the motion of something, there seems no logical necessity that it should be. When one speaks of a wave of emotion sweeping over a country, this is not only a metaphorical use of the term. The state of emotion might indeed be propagated according to laws similar to those of a wave, and in such a case one would be as much entitled to speak of it as a wave as one would if it represented actual motion. All the effects so far observed have been equally well accounted for by regarding the electron waves as the propagation of a state in the space through which they pass, the state being that of ability to direct an electron in a certain direction. This view is extraordi-

narily close to the view taken by Newton of the propagation of light which may be illustrated in the following quotation:

"Those that are averse from assenting to any new discoveries but such as they can explain by an hypothesis, may for the present suppose, that as stones by falling upon water put the water into an undulatory motion, and all bodies by percussion excite vibrations in the Air; so the Rays of Light excite vibrations in the refracting Medium or Substance . . . that the vibrations thus excited are propagated in the refracting or reflecting Medium or Substance, much after the manner that vibrations are propagated in the Air for causing Sound, and move faster than the Rays so as to overtake them . . . and that every Ray is successively disposed to be easily reflected or easily transmitted by every vibration which overtakes it. But whether this Hypothesis be true or false I do not here consider."

An alternative view, which is probably at bottom very nearly the same although superficially different, regards the wave as a "wave of probability," places where the wave is intense being places where the electron is likely to appear. This view is perhaps best under-

stood by considering the case of a beam of electrons containing a large number moving under nearly similar conditions. If the waves of the separate electrons are combined into a single wave representing the whole beam, then the results of the experiments are expressed by saying that the electrons are numerous and densely packed where the wave is intense, and sparsely distributed where it is weak. Thus considering any one electron the chance of its appearing in a particular place would be proportional to the intensity of the wave there. If it were possible to work with a single electron instead of a beam, it is reasonable to suppose that the same rule might hold, that there would be a certain chance of the electron appearing at any place to which its waves penetrated, and that the chance of its being there was proportional to the intensity at the point. This introduction of probability as a factor in the expression of a fundamental law is very characteristic of the recent trend of physics, which is moving away from the rigid determinism of the older materialism into something vaguely approaching a conception of free will. It may be objected that an electron coming from a definite place and acted on

by quite definite external forces must of necessity arrive at some definite point. The reply can be made that it is impossible to tie an electron down exactly to a definite starting-point; all you can do is to say that it must have been somewhere within a small region at a definite time. This is really equivalent to limiting fairly strictly the region in which the waves associated with the electron were originally present. Now imagine the electron as taking part in some experiment, for example, going through a thin film of metal; the waves associated with it may spread, and on the earlier view may carry the electron with them to any part of the region which they reach. It is possible to take the point of view that the particular direction in which the electron happens to be scattered is, in fact, completely determined by the exact value of the original position and velocity of the electron; but since these exact values can never be known, all that we can really predict as to the result of our experiment is a matter of probability. It is perhaps more modest not to postulate a theoretical knowledge which can never really be available, and to allow the essential uncertainty of the experiment to be indicated in the

fundamental laws by stating these in a probability form. Which view is preferred is probably mostly a question of individual psychology. To those brought up in the older school of physics the idea of a determinate motion, even though one can never know all the determining factors, will usually be the most agreeable. But it may be questioned whether this will continue to be true if atomic physics ever becomes part of the general group of ideas familiar to all educated people, and succeeding generations are brought up to regard as established and natural the ideas which they involve.

In the case of the free electron at least, it is definitely possible to construct a scheme according to which its movement is fully determinate, though in certain cases this involves a break with some of the cherished principles of the older physics such as the conservation of energy. The trouble seems to be that we have reached a scale of minuteness where the available tools are too coarse for the work of investigation. It is like a blind man trying to investigate the working of a watch by poking his finger into it. In the act of discovering the position of the parts he upsets

their movements. In ordinary physics we can use relatively delicate means of investigation. Rays of light are of course the commonest, but light as we have seen acts by the impact of its quanta, and from the point of view of the electron these quanta are violent projectiles. If we try to make them less violent by choosing rays with a smaller quanta, we find that we have chosen those of long wave-length, since wave-length and quantum energy vary inversely. But a large wave is obviously not well suited as a device for the accurate location of a small object, and so by gaining in gentleness we sacrifice precision. The same difficulty arises in a more direct form if we use other electrons as our exploring fingers. Obviously they will cause about as big a disturbance as they themselves undergo, and it is impossible to locate the position of an electron without so disturbing it that its subsequent velocity is quite uncertain. A similar result applies if we try to determine the velocity of the electron. To get this exactly we must allow it considerable space over which to range, and its position becomes correspondingly uncertain. There is, in fact, an exact reciprocity between the exactness

with which position and velocity (or more precisely momentum) can be determined. In proportion as the one becomes more exact so the other becomes more uncertain. This relationship has played an important part in theoretical physics in the last two years and seems likely to be increasingly important. It is known from its discoverer as the Heissenberg Uncertainty Relation. It represents perhaps a limit that we are reaching—the limit of attainable knowledge on the side of the very minute. But of course if anybody were to discover any probe more delicate than an electron, the argument would break down.

CHAPTER XIII

THE STRUCTURE OF THE ATOM (3): THE WAVE THEORY

THE application of the wave theory to the stationary states of an atom was part of de Broglie's original statement, and has since been modified and amplified by the work of Schrödinger. In view of the fundamental character of the energy levels in explaining atomic properties, the first test of any proposed atomic theory must be its ability to give a reasonable explanation of their existence. In the case of the hydrogen atom the wave theory successfully passes this test. This atom composed of one electron and one proton is, of course, the simplest of all. The result of a somewhat elaborate mathematical calculation is that only certain values of the energy of the atom can lead to a permanent distribution of waves. The general way in which this comes about can best be seen by regarding the

waves as travelling round the orbit. If the orbit is of such a length as to include a whole number of wave-lengths, then the disturbance returns in phase with itself and a steady state is possible. But this clearly puts a limitation on the possible sizes of orbits. To take a humble parallel it is like papering a room with a patterned wall-paper. In general, when the paper has gone round the room back to its starting-point the pattern will not exactly fit, but there are certain sizes of rooms for which it will. These correspond to the possible states of the atom. Further, it can be shown that those orbits are just those predicted on the older Bohr Theory. In actual fact the waves spread away from the orbits, and the explanation we have given must be regarded only as a general indication of what is happening. The full mathematical investigation leads, however, to the same conclusion—namely, that only certain values of the energy permit the atom to exist in a steady state. It is found, in fact, that corresponding to any steady state there are three whole numbers which determine the nature of the wave system. In hydrogen the distribution of the waves is such that there are certain surfaces permanently at

rest called Nodal Surfaces. These may be spheres with the nucleus as centre, cones with the nucleus as apex, or planes through the nucleus. The three numbers determine the number of nodal surfaces of each of the three kinds, and when they are known the form of the wave system is known also. These numbers are the numbers introduced into the last chapter as quantum numbers but with this exception that there are only three. The fourth makes its appearance in a different way which we shall speak of later. The name "quantum number," which is a heritage of the orbit theory, is justified to this extent, that the nodal surfaces to which they refer are determined by waves whose length is proportional to h, the fundamental constant of the quantum.

Not only does the calculation give the right values for the energy of the steady states of hydrogen under normal conditions, but the calculation can also be extended to the case in which the atom is under the action of electric or magnetic forces. In these cases levels corresponding to different quantum numbers which previously had the same energy, become distinct. Unfortunately for most of the

other atoms the mathematical difficulties are too great to permit of a complete solution. But from the general nature of the calculations it becomes clear that the results will be of a similar nature, namely that there will be definite energy levels determined by integral quantum numbers. These investigations show that the waves even in a steady state are not confined to linear orbits. They spread through the whole region of the atom, and indeed stretch out into space without any very definite boundary, though their intensity is small at distances from the nucleus greater than what is usually taken as the radius of the atom. There is, however, a certain tendency for the intensity of the waves to be greatest in the neighbourhood of the old orbits.

Schrödinger was able to reach these results without having to consider what physical significance was to be assigned to the intensity of the wave. All he had to postulate was that the mathematical quantity Ψ (psi) which represents the wave was something which had only one value at any one place. We have seen, however, that one way of looking at the waves for the free electron is to regard their intensity as measuring the probability of the

presence of an electron, or if many electrons are present the closeness or density with which they are grouped. This interpretation actually had its origin in Schrödinger's atomic theory. It came from an attempt to calculate the behaviour of an atom when acted upon by a wave of light. What actually happens is that the atom scatters some of the light with an intensity depending on the relation between the frequency of the light and that of the spectral lines characteristic of the atom. If the frequencies are nearly the same, an abnormally large proportion of light is scattered. It had been one of the great difficulties of the orbit theory that it did not, in fact, give this relation correctly. Schrödinger showed that it followed at once from the theory, if the electrons were treated as a continuous distribution of electric charge with density proportional to the intensity of the waves, i.e. to Ψ^2. Such a view is a startling reversal of ideas, for up till now the whole argument has tended to regard the electron as essentially an individual discontinuous charge. Perhaps the difficulty is more real than apparent. If we average over a sufficiently long time, it will not make much difference for many purposes

whether we are dealing with a continuous distribution of charge of varying density permanently fixed, or a number of discontinuous charges which are wandering about in such a way that the probability of one being in any place is proportional to the density on the other assumption. Both views will make the average amount of electricity in any small region the same in the long run.

Schrödinger's atom also supplies at least a hint of explanation of the law of frequency of emitted radiation; namely, that the frequency is the difference in the energy levels divided by h. In a stationary state the wave reduces to a simultaneous vibration of all parts of the atom which thus resembles a vibrating system such as a violin string. The fundamental law of the wave mechanics shows that the frequency must be the energy divided by h. The same is true for the atom in another steady state. Now suppose a wave to exist corresponding to the superposition of two steady states. The result will not be a steady state. It will be a vibration whose amplitude rises and falls with a frequency which is the difference of the frequencies of the steady state. This phenomenon is analagous

to "beats" in sound. These occur when two notes of nearly but not quite the same frequency are sounded simultaneously, and are caused by the rhythmical rise and fall in the intensity of vibration of the air caused by the superposition of the two trains of sound waves which sometimes cancel and sometimes rein-

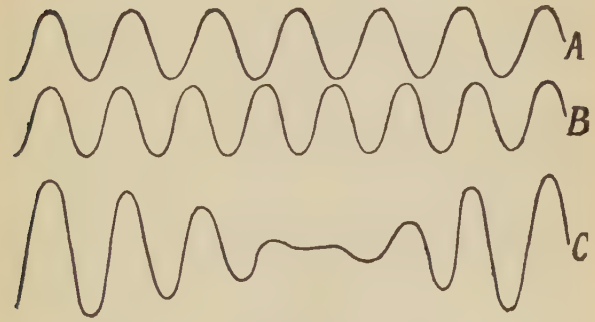

FIG. 15.

force each other. Thus the result of superposing the two trains of waves A and B of slightly different wave-length is to give the complex wave C which can be regarded as a wave whose amplitude slowly changes. The steady states being permanent do not radiate energy, but one may suppose that radiation occurs when these beats are formed, and if the

frequency of radiation is the frequency of the beats it will be given by the difference of the energies divided by h, as we have seen the experiments to indicate. This part of the theory is still rather tentative and there are several points not fully explained, but it is the only attempt that has yet met with any success as an explanation of the law of radiation and so deserves mention. How such a wave acquires its quantum particle one cannot say. Perhaps the mere existence of a wave necessarily implies a particle of suitable energy, just as a particle apparently implies a wave.

For complex atoms the waves are determined by a mathematical process which can only be interpreted geometrically in terms of space of many dimensions. This means that the waves have no physical meaning, and is perhaps the strongest argument in favour of the view which regards them as waves of condition or of probability rather than as waves of motion. But though the waves themselves fade into multi-dimensional ghosts, the probability which can be deduced from them mathematically remains a sober reality in three dimensions. If we regard the different possible stationary states of a hydrogen atom

as different modes of vibration, like the fundamental and harmonics of a violin string, then in a complex atom we may imagine a number of these modes of vibration superposed one for each electron. There will be some mutual modification, which is an expression in the new mechanics of what would before have been described as the forces between the electrons. More important still it is assumed that Pauli's principle holds, so that no two electrons can have the same quantum numbers. But the quantum numbers on the wave theory are integers which determine the type of vibration, analagous to the order of the harmonic in the musical analogy, so that Pauli's principle means that no two electrons can have the same type of vibration. The application of this principle brings us to a curious point. The complete determination of a type of vibration involves only *three* whole numbers, but in considering spectra *four* were required. The same difficulty arose with the orbit theory. Here also three numbers specify the orbit. This caused considerable difficulty in the later developments of the orbit theory; it was surmounted by supposing that the electron was more complicated than

a point charge and that it had a *spin*. The spin of a charged body gives it magnetic properties, so the new hypothesis regarded the electron as simultaneously a unit electric charge and a unit magnet. Now the fourth quantum number is found to have only two possible values, and so the facts could be accounted for by supposing that the electron's axis of spin was always at right angles to its orbit, but that the direction of spin could be with or against the direction of motion in the orbit. There is nothing on the wave theory that at all obviously corresponds to this, and the necessary extension has only been made as the result of difficult and highly abstract mathematics which are totally unsuited for verbal explanation. Dirac and Darwin have been the leading workers on this point, which has only been seriously dealt with in the last year or two. A new theory is seldom established at first in its simplest form, and we may hope that in time it will be found possible to express it in a simpler form. For our purposes we may ignore the added complication, except for the important fact that two electrons can be allowed for each type of vibration instead of one.

The remaining three quantum numbers which determine the type of vibration, or of orbit on the older view, are not equivalent. One, called the principle quantum number and generally denoted by n, is the most important. Thus in a hydrogen atom free from external disturbing influences, it alone determines the energy. The second quantum number denoted by l is governed by the rule that it is any integer less than n, a zero value being allowed. Thus if n is 3, l may be 0, 1, or 2. The electrons distinguished by a particular pair of values n and l, e.g. 3 and 2, are distinguished among themselves by the value of the third number generally denoted by m. The rule here is that m is a number positive, negative, or zero, not greater than l. Thus for $l = 2$ the possible values of $m\hat{l}$ are -2, $-1, 0, 1, 2$. A simple calculation shows that the total number of possible groupings of these subsidiary numbers is n^2. Thus for $n = 3$ they are shown as follows:

$l = 0$	1	2
$m\hat{l} = 0$	$-1, 0, 1$	$-2, -1, 0, 1, 2$

Here the total number of entries in the last line is 9 and as $n = 3$ the rule is verified. To

allow for spin the possible number is doubled and we get a total of 18 electrons whose principle quantum number is 3.

When a number of electrons have to arrange themselves round a nucleus to form an atom the general rule is that they try to occupy first those states for which the principle quantum number is small; thus in helium, which has only two electrons, they take up the two possible states corresponding to a principle number 1. The next 8 atoms in the series with numbers of electrons ranging from 3 to 10 fill up the 8 possible states corresponding to a principle quantum number of 2. Now it is found that the formation of a complete group corresponding to the exhaustion of the possibilities inherent in a principle quantum number results in a peculiarly stable arrangement. Thus both the 2nd element helium and the 10th neon are inert gases which show no chemical affinity and are difficult to ionize by removing an electron. A similar result occurs in many cases when the possibilities of one of the value of the 2nd quantum number are exhausted. Thus in the atoms succeeding Neon when the additional electrons are being built into the group characterized by $n = 3$ a

state of great stability is reached when the possible states associated with $l = 0$ and 1, have been exhausted. A glance at the table shows that this involves four possibilities, and hence allowing for spins, 8 electrons. Thus the atom with 8 electrons more than neon is also an inert gas, namely argon. After this an exception to the rule occurs, for the next electron to be added takes up a state with principle quantum number 4, although the group with *n*3 and *l*2 has not been filled. It is not yet possible to give an exact theoretical reason for this, although considerations are known which make it seem not unreasonable. Similar complexities occur at further stages in the table of elements.

We are thus led to the following view of the structure of the more complicated atoms. As we go along the series beginning with hydrogen the charge on the nucleus increases by 1 unit for each successive element reached. Each successive element has thus an additional electron to dispose of, and it does so as a rule by gradually filling up the possibilities first of having a principle quantum number 1, then 2, and so on. As an exception at certain stages instead of filling the last sub-group

corresponding to the largest value of l for the principle quantum number which it is using, it jumps to the earlier sub-groups of the next largest value of n. When this happens the numbers which have not been used have to be filled in at a later stage, i.e. among elements of larger atomic number. This scheme, which was first proposed by Bohr on the basis of the older orbit theory, is remarkably successful in explaining the chemical and spectroscopic peculiarities of the various elements and is the physical basis underlying the periodic table discussed in Chapter III.

The peculiarity of the wave view as contrasted with that of orbits is that the waves exist throughout the whole of a region roughly coextensive with the size of the atom as determined by its packing in crystals, and are not, as on the older view, confined to definite paths. Since the waves of the different electrons, in so far as they can be distinguished, are overlapping, one might suppose that the electrons had lost their identity and merged into a general diffuse mass. But this view is probably wrong, for the very equations which lead to this apparent spread include terms which are only intelligible as representing

forces between individual point charges. What is perhaps even more important, the exclusion principle on which the whole scheme is based is in its very essence a statement of the stubborn individuality of electrons and of the impossibility of merging them together.

One curious feature of the whole scheme (and this applies equally to orbit and wave theories) comes out in considering the transitions between stationary states. If, for example, an electron is removed from the inside of an atom, the atom is left in a condition of excess energy. On the orbit view another electron will come in to take its place from one of the outer layers, and the excess energy is radiated in a quantum giving one of the characteristic X-ray lines which Moseley studied. On the wave theory some rearrangement of the vibrations takes place resulting in an equivalent effect. Now in general there are many ways in which this can happen, for there will generally be electrons of many different energy levels which can take the place of the one removed. The question arises, what determines the change that actually occurs in a particular atom and hence the particular frequency which that atom chooses

to emit? Any actual experiment involves using a large number of atoms simultaneously, and then it is found that the different possible spectra lines are emitted with different strengths. It is conceivable that each separate atom emits all the lines with varying intensities, but such a view seems very hard, if not impossible, to reconcile with the unitary nature of the quanta of energy in the different sorts of radiation. If, for example, one line is two-thirds as strong as another, is it to be allowed to emit two-thirds of a quantum? Questions of this type are now being discussed, and it is too early to give any definite answer. Personally the author feels that it is more in agreement with the general conception of atomicity whose striking triumphs we have followed in these pages, to suppose that any one atom in such a case emits only the one quantum. If one is asked what determines which frequency the atom chooses, one can only plead complete ignorance, or what is practically equivalent, say that it is a matter of probability. There is a tendency to believe that such ignorance may represent a permanent limitation of knowledge. But these theories are still so recent that it seems

rash to assert dogmatically that it will be for ever impossible to devise an experiment which would enable one to predict which of several possibilities an atom would choose.

CHAPTER XIV

ELECTRONS IN CHEMISTRY

It was early seen that the electron theory of the atom affords a means of giving at least a qualitative explanation of the main facts of chemistry. The general idea which has been developed by a series of writers, is that certain atoms can readily lose electrons, while others are eager to gain them. If atoms of these different kinds are brought together, a transfer of electrons may be expected to occur. As a consequence, some of the atoms will have on the whole a positive charge and others a negative, and these oppositely charged bodies will attract each other in accordance with the ordinary law of electricity. The idea that the atoms of a chemical molecule can be divided into two groups which are endowed in some way with opposite properties is a very old one in chemistry, and indeed much antedates the discovery of the electron. The very large

class of chemical compounds known as salts, of which common salt is a typical example, afford good evidence of this. They consist essentially of a metallic, and a non-metallic part, and can be looked upon as the result of a combination between an acid, which is a compound wholly formed of non-metallic elements, and a base which is a metallic oxide modified by combination with water. When the salt is formed, water is eliminated and takes with it the oxygen from the metallic oxide, leaving the metal in combination with the residue of the acid, called the Acid Radical. The dual nature of these compounds is well shown by their action in solution. They are all more or less conductors, and in electrolysis the metal moves to the negative pole showing that it has a positive charge, while the acid radical moves in the other direction and is therefore negative. The metals are therefore described as electro-positive elements, and the elements which form acids as electro-negative. This description is also shown in other ways. Thus the metallic atoms have, as a rule, a comparatively small ionization potential showing that they can be deprived of an electron without much difficulty. On the

other hand, atoms of the electro-negative elements when separated in the gaseous state show a tendency to acquire extra electrons and appear as gaseous ions with a negative charge.

As soon as some insight was gained into the arrangement of the electrons in the atom, it became possible to bring the ideas of atomic structure into line with the chemical theory of valency. The fundamental idea is that chemical combination is a result of the action of those electrons which are least firmly held to the atom, and which are pictured as forming its outer layer. On the theory of the last chapter an atom of one of the inert gases contains in its outer layer a completed group or sub-group. Now the next atom in the periodic table is always one of what is called the alkali group, e.g. sodium, which is characterized by being extremely electro-positive but has only a single valency. The natural explanation is that the electron which such an atom possesses over and above those of the previous inert gas, is comparatively loosely held. Conversely the atom immediately preceding an inert gas is extremely electro-negative but also has only a single valency.

We suppose, therefore, that such an atom—as, for example, chlorine—is anxious to obtain an additional electron to enable it to complete its group. The union of an atom of sodium and chlorine to form a molecule of common salt is thus pictured by supposing that the sodium has lost an electron to complete the shell of the chlorine. Thus each is left with a completed shell, but with the difference that in the case of the sodium the number of extra nuclear electrons is one less than the nuclear charge, while in the case of chlorine it is one greater. Accordingly there is an electrostatic attraction between the two which holds the molecule together. This idea may be pressed further. The next atom to sodium is electro-positive and divalent, and the one after trivalent. Thus the former, magnesium, will combine with two atoms of chlorine, and the latter, aluminium, with three. The natural interpretation is that magnesium has two electrons to spare outside its completed group and can thus complete the groups of two chlorine atoms, while aluminium can hold three. This view is in agreement with what at first sight seems a curious fact; namely, that though sodium can only combine with

one chlorine it does so with more vigour than aluminium combines with its three. One may suppose that the three aluminium electrons are on the way to form a new group of their own and might indeed with a little encouragement attract additional electrons to complete it. Actually aluminium in a few compounds shows signs of electro-negative behaviour. At the electro-negative end similar effects are found. Thus oxygen, which occurs two places before an inert gas, can combine with 2 atoms of sodium or 1 of magnesium, while 2 aluminium will combine with 3 oxygen atoms. In each case the excess electrons of the metals are just sufficient in number to fill the gaps in the electro-negative atoms.

In the first two rows of the periodic table the inert gases succeed each other at intervals of 8 places, so the rule is equivalent to saying that the outer electrons of the atoms of a compound add up to 8 or a multiple of 8. As it is in the first two rows that the regularities referred to are most strongly marked, the number 8 has played a very important part in chemical theory. On the view given in the last chapter it represents the number of electrons required to complete the sub-groups for

which $l = 0$ and 1. For the first row this also marks the completion of the whole group corresponding to the principal quantum number 2. For the elements beyond these rows things get rather more complicated because, at certain places in the table, sub-groups which had been passed over in favour of those of a higher principal quantum, have to be filled, as it were underneath the surface. Several atoms may thus succeed each other with the same outer electrons, and therefore closely similar chemical properties.

It is worth noticing that this view of chemical combination is in full agreement with the theory of valency described in Chapter III. The "bond" appears as the transference of an electron, and the tags of string by which we visualized it appear as *either* an unneeded electron *or* a place for an extra one. For this class of compound a better image would be a number of projecting spikes on one class of atom fitting into holes on the atoms of the opposite kind. The inert gas is thus the type of a saturated compound, and the absence of chemical activity in these elements is fully explained. When a molecule of this kind is dissolved in water the electrons remain with

the atoms to which they have been transferred, but the electro-static attraction is overcome and the atoms drift apart as charged ions. Since the presence of water between two electrical charges does, in fact, diminish the attraction between them to $\frac{1}{80}$ of its original value, this result is not surprising, and we can see why solutions of salts in water conduct well, while the same salts in some other liquids are insulators.

Compounds of this class are sometimes called Heteropolar. One part is different from the other as positive is different from negative. But there are other compounds which do not fit in with this scheme as it stands. For example, 2 atoms of chlorine can combine to form a molecule, and so can 2 of oxygen. Here both atoms of the compound are equally deficient and neither can supply the electrons required by the other. To get over this difficulty it has been supposed that in certain cases electrons may be *shared* by 2 atoms so that they count towards the groups of both. Thus if 2 electrons are shared between the chlorine atoms, the 14 electrons can be made to do the work of 16 and provide two groups of 8. Similarly with oxygen, if 4 are shared the 12

electrons become equivalent to 16. In such compounds the 2 atoms are on an equal footing and the compounds are called Homopolar. Numerically far the largest class of compounds is formed by those of carbon, for they include the hundreds of thousands of organic compounds known, many of them of very great complexity. It is in this class that the theory of valency has had its greatest success. Starting from the basis that carbon has 4 valencies, it has been possible to build up structural formulæ, as they are called, showing the way in which the atoms are linked together. The pictures so formed of the molecules have been of the greatest value in predicting chemical properties. For example, atoms near together in the molecule are found to be more likely to react jointly with an external reagent than those far apart. Even the shapes deduced for the molecules have been confirmed by the X-ray study of organic crystals. The power of the valency theory over carbon compounds, and also their variety is probably connected with carbon being the middle element between two inert gases. Thus it can get its closed group either by losing 4 electrons or by gaining 4.

In many cases the carbon atoms are arranged in chains which may reach to 20 or more members. In these chains the carbon atoms are linked together in what is apparently a homopolar manner. Whatever the nature of the bond, it is apparently shared equally by the 2 atoms which it connects. This bond is regarded as a sharing of a pair of electrons. Sometimes a special type of bond occurs which may be regarded as the sharing of 4 electrons. This is spoken of in chemistry as a double bond and on the valency picture implies the tying together of two pairs of tags. But so far from a double bond being twice as strong as a single bond it is actually weaker. On the electron view this is not surprising, because if 4 electrons are to be crowded together between the 2 carbon atoms their mutual repulsion will be large and will be all the time tending to push them apart and so sever the bond.

Triple bonds are also known and presumably involve the sharing of 6 electrons. Long chains are only formed from the strong single bonds with perhaps an occasional double or treble one. To complete the necessary number of electrons each atom in a chain of single bonds requires 2 extra from outside. These

are supplied by other atoms attached at the side of the chain. They are often atoms of hydrogen. This is the case in the group of compounds which compose mineral oil and are known as paraffins. Besides these homopolar linkages, organic molecules sometimes contain atoms which are attached by a heteropolar bond and undergo dissociation. For example acetic acid (vinegar) can combine with metals to form salts very similar to those of inorganic acids.

A peculiar and very important type of linkage is what is technically called a benzene ring. This is a structure of 6 carbon atoms which forms a fundamental part of the molecules of the coal tar dyes and of many other organic substances of technical importance. An immense amount of thought and ink has been expended on controversies as to the exact method in which these 6 atoms are linked together. It is certain that they somehow form a closed ring, and it is extremely probable that all the atoms of the ring are equivalent. Each atom requires an additional electron to satisfy its affinities. On the whole the most probable explanation of this structure is that each bond involves the sharing of 3 electrons between the atoms it unites.

It is difficult to explain the idea of an electron shared between 2 atoms on the orbit theory, and the theories we have been describing grew up quite independently of the former, and indeed rather as rivals to it. They were, however, quite unable to explain spectroscopy, and were not regarded with much favour by the more mathematical physicists. The coming of the wave theory gives reason to hope that it will be possible to devise a structure of the atom which will be equally satisfactory both to physicists and to chemists. During the last year the work of Heitler and London shows considerable promise of adapting the wave theory of atomic structure to chemical requirements. Unfortunately the mathematical process used is very difficult and abstract, so that it is not easy to express simply the ideas involved. They consider the homopolar type of combination, the theory of the heteropolar type being probably not very different on the wave theory from what it was on the older view. It appears on the wave theory that when two atoms approach each other very closely, there may in certain cases be a rapid interchange of electrons backwards and forwards between the two, and

that when this occurs it is equivalent to a force drawing the two atoms together. This force is usually more important than the ordinary electric attractions and repulsions between the constituent particles. Such an interchange turns out only to be possible when each atom has an unpaired electron. That is when at least one of the "cells" determined by three quantum numbers which might contain two electrons of opposite spins has only a single occupant. Only those electrons which are not paired in their own atom act in this way, and the process is to some extent analogous to the completion of a sub-group, except that the pair of oppositely directed electrons takes the place of the group of 8. It is very unfortunate that no simple translation can be made of the idea of electronic spin into the wave theory, as the importance attached on this theory to completing a pair implies that it is in some way the spin which is responsible for the nonpolar type of chemical linkage. Since the number of single electrons in an atom is limited, so also is the number of other atoms with which it can combine in this way, and the general idea of valency is kept. The number of such single electrons is found in most cases

to be in agreement with the usually accepted chemical valencies, and in some cases the theory explains certain differences in behaviour between otherwise similar atoms in the same group of the periodic table. It appears from the theory that 2 atoms, even when they have the necessary unpaired electrons, will not combine every time they meet. There are two possible modes of approach, one causing a repulsion and the other attraction and combination. One may think of these as corresponding to two possible relations between the spins of the single electrons in the atoms, which may be in the same or opposite directions. While this theory is still at a very early stage, and will very likely need considerable modification before it is finally satisfactory, it is interesting as showing that it is possible to explain some of the facts of chemistry by a theory originally invented purely to explain physical laws. Chemistry is a very complicated subject, and it will very likely be necessary to consider types of union other than the two classes we have mentioned. For example the molecules of many salts take up a certain number of water molecules when they get the chance. This water is called

water of crystallization. Water is a compound whose electrical properties show that it has a positive charge at one end and a negative at the other. If parts of the salt molecules are charged, they may attract the end of the water molecule which has an opposite charge, though both salt and water molecules are neutral *as a whole* and neither may have any electrons to spare for bonds. Possibly also the two types of combination we have considered are not to be regarded as sharply divided in practice, but rather as ideal types to which actual compounds approximate. The whole subject is one in which considerable advance is probable in the near future, and one may hope that it will not be so very long before the grouping of atoms in a molecule can be shown to be the consequence of laws known to exist from purely physical evidence.

CHAPTER XV

GENERAL CONCLUSIONS

In the course of this book we have seen how the idea of division into units appears in almost every branch of physics and chemistry. There are units of matter, of electricity, of energy. The developments of the present century have made this idea seem more and more fundamental in the universe. Some of the laws of nature which formerly seemed the most important, such as gravitation, have been seen in the light of relativity to be truisms. In almost any conceivable universe they must be as we find them. It seems otherwise with atomicity. There is no apparent reason why the world should have been constructed in this way, and the fact that it has been so constructed is perhaps the supreme discovery of science. Not only is the existence of small equal units important when these units can, in fact, be isolated, but it is the explanation

of another large group of laws, which include many of those of the greatest practical importance. These are the laws called "statistical." They depend for validity on the curious fact that the most irregular chaos that can be conceived has by its very irregularity an order of its own.

Consider, as an example, life insurance. It is known from past observation how many people in the country die each year at various ages. If ten thousand people take out life policies with a particular company, the company can calculate from these observations how many will die at the various ages, provided the people are a true random sample of the population. It is precisely *because* they are a random sample that the calculation is justified. If they have been specially selected in any way the conclusion needs to be modified, and more data will be required before an accurate prediction can be made. Thus selection by chance produces a law which a rational selection would destroy. In the same way with the molecules of a gas in a given vessel: they are moving about at random in all directions, bumping into one another and altering one another's velocities. These velocities are

a measure of the temperature, but they are unequal and perpetually changing, and the temperature represents only a mean effect. Now if a portion of this gas is removed, then since the molecular velocities are distributed at random, the sample will contain its fair proportion of fast and slow molecules and the mean will correspond to the same temperature as that of the whole. Thus once such a group of molecules has been long enough in the vessel to reach a proper state of chaos, it is impossible by simply dividing it to get two portions of different temperatures. This is one simple case of the very important principle known as the Second Law of Thermodynamics.

Now all laws of this kind necessarily involve very large numbers of units. An insurance company which depended on insuring half a dozen lives would be a very risky concern. For as few things are more certain than the profits of insurance on a large scale, so few are more uncertain than an individual life. The security of many of the laws of physics rests on the enormous number of units which are contained in even the smallest bodies of everyday life, thus many laws of physics

which contain no mention of atoms in their statement, are only true because, in fact, atoms are small and therefore numerous. A peculiarity of these statistical laws is that, though the phenomena which they describe depend on definite laws, the nature of these laws does not matter. Thus in the example we have considered the interchange of velocity between any two molecules depends greatly on the nature of the forces between them, but whatever the forces the statistical distribution of velocities is the same in the end. The importance of laws of this kind can hardly be exaggerated, yet they are solely the consequence of the unitary nature of the world, and would not seem true to a being constructed on so small a scale that he could watch individual molecules. But probably this very fact makes it impossible for such a being to exist.

Yet in spite of the importance of units, and the discontinuous view of the world which they necessarily lead to, there is another side to the question. We have seen how it has been found necessary to associate waves, not only with the light quanta, but with electrons as well and presumably with all particles. Now waves essentially imply continuity.

They involve the continuous propagation of something, even if it is only a probability. The efforts of the nineteenth century to reduce everything to the properties of a continuous medium, and those of the twentieth to explain it by particles alone, seem equally to have failed. However distasteful the idea, we are apparently forced to admit the two on an equal footing. Somehow they are both there in the world and neither will yield. The relation between them is still a matter of the greatest difficulty and no full solution has yet been reached. In any case that can be tested by actual experiment, there is seldom any doubt as to how to use the two conceptions, and we may hope that it will be possible to see them as two complementary halves of a single truth.

In contemplating a world constructed of electrons, protons and the quanta of radiation we are conscious of a great simplification, which is the chief æsthetic compensation for the difficult nature of the ideas which have to be introduced to explain their behaviour. Three "things" and a few rules replace the vast diversity of the apparent world. But there remain two curiously arbitrary features.

One is the difference in mass between electron and proton. This does not seem *a priori* a necessary feature of the scheme, and even if it were, it seems very strange that one should be (about) 1,844 times the other. It is such a queer number for Nature to choose, if it had been 3 or 4 or π it would somehow have seemed more natural. So far there is no explanation. Perhaps none is possible, but a recent paper by Eddington attempts an explanation of the second arbitrary feature which is not unlike it in nature. It is this. From the charge on the electron, the velocity of light and Planck's "h" a composite quantity [1] can be derived which is a true number. Unlike the values of the separate quantities it does not depend on the units used to measure them, provided, of course, they are the same for all three quantities. Thus, while the velocity of light is 186,000 if measured in miles a second and 300,000 in kilometers a second, this quantity is 137 and a fraction in all cases. It has thus a real physical meaning like the 1,844 we have just been considering. Now Eddington's argu-

[1] It is $\frac{ch}{2\pi e^{2}}$

ment is based on the idea that "e" is a measure of the electrostatic repulsion of two electrons, while by the Pauli exclusion principle "h" is a measure of the size of the cell which is only allowed to contain one electron. It therefore also expresses in some way the tendency of electrons to keep apart. If these are really expressions of the same physical fact there must be a relation between the numbers representing them. By an extremely abstruse mathematical analysis he was able to reduce the relation to one of geometry involving the counting of a certain set of points. There are 136 of them. The agreement is not exact, and the error is greater than the probable experimental errors in the measurements of e, h and c, but is not outside the bounds of possibility. The experiments will probably be repeated, and it will be very interesting to see if the suggestion is confirmed.

In the first chapter we started by postulating a crude substance, commonsense matter. In the course of the book the reader will have realized that this commonsense matter is not at all a matter of course. Its solidity seems to dissolve into a whirl of electrons and pro-

tons. Even its mass is not constant, for it may lose some when it radiates energy, nor is it the only thing which has mass, for this is a property of all forms of energy and in particular of light (visible and invisible) which in other respects differs widely from matter. Perhaps its most permanent property is the number and charges of the electrons and protons composing it. Even these may disappear in the stars, if the view of Jeans and others is correct. The nuclei, which contain the great bulk of the mass of a piece of matter, occupy a negligibly small part of the volume. For a man's body their combined volume would be an almost invisible speck. The rest is "occupied" by the circumnuclear electrons. While the newer theories are reluctant to assign any very definite size to these electrons, they certainly do not "fill" this space in any ordinary sense, for it is quite possible to shoot electrons through it without producing any permanent disturbance, though such *may* result. Thus the view expressed by the adherents of the orbit theory that matter is mostly empty space is at least not far from the truth. In fact, we are even worse off than they, for our electrons have no definite posi-

tions, only probabilities, and we are left with a world mostly holes, occupied by things which are nowhere in particular!

In these circumstances one can hardly escape considering how far the matter of physics can claim to be "real," however much one may shrink from embarking on philosophical considerations, for which a scientific education and habit of mind is an inadequate preparation. It would seem to the writer that there are several stages of reality. What one actually perceives has an instant reality at the moment of perception from which there is no escape. It does not matter if it turns out afterwards to have been a dream or hallucination, at least the perceiving was real. The next stage comes when one tries to piece together a number of perceptions and form an object. Thus what one calls a chair is really a synthesis of a large number of separate impressions, visual and tactual, of that chair together with memories of what one judges to have been similar objects. To make the point more definite: What one actually sees from a given point of view is a perspective picture of the chair on the retina, slightly different for the two eyes because of their

slightly different view-points. These pictures change as one approaches the chair, and instead of trying to deal with them as a series, like a reel of cinematograph film, the brain creates a conception of a three-dimensional rigid body. The truth of Euclidian geometry means that if this is done according to certain rules, the conception will not need to be disturbed to fit perceptions from any other standpoint. But the chair may be a reflection in a mirror; in such a case commonsense would say it was not "real." This is because if you tried to approach and touch it you would receive sensations which did not fit the imagined shape. It is necessary to make a more complicated assumption, and suppose a mirror and a "real" chair somewhere else.

Now all this is just to show that the chair of commonsense, as opposed to a single perception of it, is a geometrical abstraction erected in the mind to unify the perceptions and make it possible to act on them in a rational and useful manner. My contention is that the physicist's chair of electrons and protons is just on a par with this. It is a different abstraction and stresses different

points; it is suited as a guide for different kinds of action, but as far as reality goes, there is nothing to choose. The physicist wants a scheme of things which will enable him to predict the result of any conceivable experiment. The result of an experiment means a perception on the part of somebody, and the necessary conditions are known from the perceptions of the man who set the experiment up. We need a rule to get from one set of perceptions to the other. This rule may be a mathematical law connecting symbols, but there must be as well a sort of dictionary which will translate the initial perceptions into the appropriate symbols at the beginning of the calculations, and the final symbols back into perceptions at the end. It is the necessity for this dictionary which makes physics definitely and for always more than a special branch of mathematics. But though a mathematical rule will do for prediction, and is, indeed, the final aim of the science, it is by itself a very unsatisfactory tool for research when the subject is in the unfinished state. The discovery of fresh phenomena must be a tentative process, and the researcher is immensely helped in making a suitable choice

of what to try next if he has in his mind a working model, however crude, of what is going on. This suggests by analogy possible experiments and lines of attack, which the formal mathematical statement of what has actually been proved so far, is often powerless to do. The conception of electrons and protons bears the same relation to the ultimate mathematical equations that the commonsense chair bears to the blue print from which it was made. Both conceptions have equal claim to reality so long as no perceptions arise which are inconsistent with them.

Experiments such as the Wilson tracks and X-ray scintillations bring out very clearly the claim of atoms to commonsense reality; it seems unreasonable to deny reality to an entity which leaves its signature scrawled across the air like a miniature cloud writer. As long as we keep to atoms there is little need to alter any ordinary conceptions. They pack together in crystals in definite arrangements like spheres of definite size. In X-ray analysis we "see" the atoms in a sense very little different from that in which one may see bacteria under the microscope. We can say with certainty which atoms are neigh-

bours in a molecule and which are far apart. There is altogether an air of order and tidiness about their behaviour. When we go a stage further to the electrons which compose them, things become much vaguer. If they have definite places and orbits in the atom, they are apparently permanently inaccessible to direct observation; our finest instruments are too coarse. To describe the behaviour of the waves which accompany them in the atom, space of many dimensions is required. Yet even here some vestiges of decent behaviour remain. There is a sense in which some electrons are near the nucleus, and some farther from it, they have certain favourite haunts. They retain their individuality by their quantum numbers. The free electron is better, its waves are in three dimensions, and if its position or velocity are necessarily rather uncertain, the uncertainty is seldom enough to matter.

We hardly know enough yet of the structure of the nucleus to say whether it will prove amenable to ordinary geometrical ideas or whether its properties will need more abstract treatment. It is the least known part of the atom, and probably the one where knowledge

will lead to results of the greatest practical importance, for this is where atomic energy and the transmutation of the elements are to be sought.

From the philosophical point of view the most important feature of the recent quantum mechanics is its strong trend away from determinism. Since the time of Newton, it had been taken almost for granted that, at least in dead matter, every particle moved in obedience to exact and definite laws. It was supposed that if the initial position and velocity of every particle of a group free from outside influence were known exactly, and if the proper laws had been found, it would be possible, at least in theory, to calculate the position of each particle at any later time. The whole behaviour of the system was determinate. It is true that this determinism was modified in practice because no system is ever free from outside influence, and the task of calculating the motion of the billions of particles in the minutest speck of matter was hopelessly beyond human possibility. Still, the theoretical possibility was believed to be a real truth, and it obliged those who wished to believe in the free will of human beings

to suppose some profoundly fundamental difference between the behaviour of the atoms in a man's brain or nerves, from that of the same atoms forming part of dead matter.

The newer view makes this unnecessary. Most of the laws of atomic physics are expressed as probabilities, which, of course, become certainties when a sufficient number of independent events are concerned to make statistics apply. For example, there is a certain chance of a given radium atom dissociating into helium and radon in the course of to-day; if a cathode ray strikes an atom there is a certain chance of its ionizing it. Now, of course, events of chance are no new thing. Which face of a die would come up, is best expressed as a matter of chance, but this does not interfere with determinism, because we have excellent reason to believe that if, in fact, one knew how the die lay in the dice-box, and just how it was thrown, the face which came up would be determined by the definite laws of ordinary dynamics. The "chance" in this case is merely an expression of our ignorance of the details of the motion. A game of chance is indeed devised so that the event on which people are to bet is deter-

mined by causes too small to be controlled. If a roulette board were always spun at exactly the same speed, and the ball thrown in by a sufficiently accurate machine, it would always come to the same number, but the accuracy needed would be so enormous that it is entirely outside human control, and chance appears as a consequence of the uncertainty of the croupier's movements.

On the old view this same type of argument should hold with atomic events. If we can't tell whether a radium atom is going to break up to-day or a thousand years hence, it is because we don't know enough of what is going on in the nucleus of that particular atom (or perhaps in its surroundings). It is only a question of ignorance of necessary data, physicists of the older school would say. But here is where the essential difference comes. As long as there was no theoretical limit to the accuracy with which the initial conditions could be measured, determinism had a meaning. In any given case one could hope by increasing refinements to approach nearer and nearer to the truth, and eventually to reach a degree of accuracy which would, for example, make a prediction about some particular

radium atom a matter of certainty. On the new view there *is* a theoretical limit to the accuracy of the determination of the initial conditions. If the position of a particle is very accurately determined, its momentum is very uncertain, and conversely. The product of the two uncertainties is always round about "*h*." Now "*h*" is very small, and this restriction is only noticeable on an atomic, or indeed electronic, scale, but there it matters a great deal. This cuts the bottom from under the argument for determinism. Even if exact laws could be devised to replace the present probability ones, the power of checking them has disappeared. We can never tell if they are really true, because the inevitable uncertainty of experimental measurements is so great that the prediction of what should happen if the law held can never be exact. It seems at present likely that it is possible to frame exact laws equivalent to the probability ones. Whether it is worth doing so is another matter, largely a question of the psychology of the thinker, but in any case since such laws could never be tested, their existence on paper would be no evidence for a real determinism in nature.

On the other view there is an inherent uncertainty or power of choice in the world, but with this proviso, that the power of choice is exercised in such a way that in the bulk certain average laws are obeyed. Certain events are regarded as "equally probable" choices of Nature. There is thus no physical argument against free-will, whatever may be the metaphysical objections. A person's free will might control the events in a few key atoms which would in turn control the future history of the brain and body. Undoubtedly living matter, and perhaps the brain most of all, is in a very delicately balanced state of equilibrium, so that it is quite conceivable that the behaviour of a critical electron in a critical atom might control the course of events in the brain and so the behaviour of the body. If this degree of control is thought too slight, we may follow Eddington in supposing that in the brain the law of averages is suspended. Events which would ordinarily be regarded as "independent" may cease to be so, and instead of being distributed at random among their various possibilities may be grouped in an ordered manner. Such a view postulates a considerable difference between living and

dead matter, or at least between conscious and unconscious, but not perhaps more than ordinary experience would suggest. It is a remarkable instance of the unity of thought that a study apparently so remote from human emotion as atomic physics, should have so much to say on one of the great problems of the soul.

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Popular Works. A good exposition of one of the most important of the physical principles underlying this work is given by Wood's *Joule and the Study of Energy* (Bell, 1*s.* 6*d.*). A good short account of the whole subject is given by Andrade in *The Atom* (Benn, 6*d.*), and the development of the idea of discontinuity in physics is graphically described by Sir Oliver Lodge in his *Modern Scientific Ideas* of the same series. A more detailed work is the *ABC of Atoms* by Bertrand Russell (Paul, Trench, Trübner & Co., 4*s.* 6*d.*), which deals especially with the orbit theory of atomic structure. Sir William Bragg's *Concerning the Nature of Things* (Bell & Sons, 7*s.* 6*d.*) is a delightfully written book which deals very largely with atomic physics, including accounts of experiments and common phenomena which are explained by them. Eddington's *Nature of the Physical World* (Cambridge Press, 12*s.* 6*d.*), one of the most remarkable books of recent years, is a masterly account of the subject, especially in its astronomical and philosophical aspects. In the present series Soddy's *Matter and Energy* and Meldola's *Chemistry*

each deal in a fuller manner with part of the subject matter treated in this volume.

More Advanced. Of books somewhat more advanced but which use only a little mathematics, so that they would be intelligible to a non-mathematical reader, we may mention the following: Millikan's *Electron* (Chicago University Press, 10*s.*); this deals largely with the evidence for the individuality of the electron, and the measurement of its charge. Sir William Bragg's *Introduction to Crystal Analysis* (Bell, 12*s.*) gives a very clear and up-to-date account of the arrangement of atoms in crystals. Sir J. J. Thomson's *Electron in Chemistry* (Chapman & Hall, 10*s.* 6*d.*) is an explanation of chemical combination and valency in terms of electrons. Midway between this class and the next comes Crowther's *Ions, Electrons and Ionizing Radiations* (Arnold, 12*s.* 6*d.*). This is an excellent book of the text-book type suited for students with a sound knowledge of the older physics. Darrow's *Contemporary Physics* (Macmillan, 25*s.*) is a good discussion of about this degree of difficulty of a number of problems.

Advanced Books, mostly of a mathematical nature and intended primarily for researchers and teachers. Of general accounts the best in English are Sommerfeld's *Atomic Structure and Spectral Lines* (English translation, Methuen, 32*s.*) and Andrade's *Structure of the Atom* (Bell, 30*s.*). The standard book on radioactivity is Rutherford's *Radioactive Substances and their Radia-*

tions (Cambridge University Press, out of print). A series of monographs on various aspects of atomic physics is published by Longmans. *X-rays and Crystal Structure* by Sir William and Prof. W. L. Bragg is the standard book in English on this part of the subject (Bell, 21*s.*), as is Aston's *Isotopes* (Arnold, 10*s.* 6*d.*) for the subject indicated in its title.

Wave Mechanics. Almost all the above books describe the older orbit theory of the atom. At present the only popular account of the wave mechanics, apart from the present volume, is Sir J. J. Thomson's *Beyond the Electron* (Cambridge University Press, 5*s.*). This deals only with the waves of the free electron. Blackie & Son have published English translations of some of the original papers of de Broglie and Brillouin (*Wave Mechanics*, 15*s.*) and of Schrödinger (*Collected Papers on Wave Mechanics*, 25*s.*), but these are, of course, highly mathematical, and, as is inevitable in the development of a new theory, somewhat tentative. A shorter connected account of the wave theory of the inside of the atom is contained in Schrödinger's *Four Lectures on Wave Mechanics* (Blackie, 5*s.*), which though mathematical is very clear and concise. *Wave Mechanics* by Flint (Methuen, 2*s.* 6*d.*) gives a general (mathematical) account of the main points. A recent translation (Constable & Co.) of *Wave Mechanics and the New Quantum Theory* by Haas gives an excellent account of the present state of the theory.

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